ARMY RESEARCH LABORATORY

Practical Aspects of Numerical Simulations of Dynamic Events: Material Interfaces

by Daniel R. Scheffler and Jonas A. Zukas

ARL-TR-2302 September 2000

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.

Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5066

ARL-TR-2302 **September 2000**

Practical Aspects of Numerical Simulations of Dynamic Events: Material Interfaces

Daniel R. Scheffler
Weapons and Materials Research Directorate, ARL

Jonas A. Zukas
Computational Mechanics Consultants, Inc.

Abstract

The use of finite-difference and finite-element computer codes to solve problems involving fast, transient loading is commonplace. A large number of commercial codes exist and are applied to problems ranging from fairly low to extremely high damage levels (e.g., design of containment structures to mitigate effects of industrial accidents; protection of buildings and people from blast and impact loading; foreign-object impact damage; design of space structures to withstand impacts of small particles moving at hypervelocity, a case where pressures generated exceed the material strength by an order of magnitude). But, what happens if code predictions do not correspond with reality? This report discusses various factors related to material interfaces in Lagrangian and Eulerian shock wave propagation codes (hydrocodes), which can lead to disagreement between computations and experience. Companion reports focus on problems associated with meshing and constitutive models and the use of material data at strain rates inappropriate to the problem. This report is limited to problems involving fast, transient loading, which can be addressed by commercial finite-difference and finite-element codes.

This report has been accepted for publication in a future volume of the *International Journal of Impact Engineering*.

Acknowledgments

The authors would like to thank Drs. Eugene S. Hertel, Jr., and Raymond L. Bell of Sandia National Laboratories for providing the input decks and examples for their balls-and-jacks problem that was used to demonstrate various interface reconstruction algorithms. The authors would also like to thank Dr. Steven B. Segletes, who served as technical reviewer for the original journal paper, and Mr. Stephen Schraml, who served as technical reviewer for this technical report version of it. Their thorough reviews and comments helped improve the report.

INTENTIONALLY LEFT BLANK.

Table of Contents

		Page
	Acknowledgments	iii
	List of Figures	vii
	List of Tables	ix
1.	Introduction	1
2.	Lagrangian Calculations: Influence of Contact Surfaces on Solutions	3
3.	Eulerian Calculations: Effects of Material Interfaces on Solutions	15
4.	Conclusions	29
5.	References	31
	Distribution List	37
	Report Documentation Page	45

INTENTIONALLY LEFT BLANK.

List of Figures

Figure		Page
1.	(a) Lagrangian Computational Grid and (b) Eulerian Computational Grid	2
2.	Typical Lagrangian Contact Interface Showing Master- and Slave-Node Designations	4
3.	Comparison of Eroding Slide-Line Options on Numerical Results for a Deep-Penetration Problem	8
4.	Example of Extreme Distortion in a Lagrangian Calculation	9
5.	Lagrangian Calculation Before and After Rezoning	11
6.	Overlay of Computed and Experimental Hole Profiles for Steel-Steel Penetration, $V_s = 3.114$ km/s	12
7.	Damage Due to Sphere Impact at 30°	13
8.	Penetration of a 50-ply Aluminum Target 15 μs After Impact	14
9.	Stages of Penetration of an L/D = 5 Aluminum Rod Striking a Thick Aluminum Target at 6 km/s	16
10.	Residual Penetration by Eroded Mass Points	17
11.	A Typical Plane-Strain HELP Code Simulation Compared With Experiment	19
12.	The Balls-and-Jacks Problem Using the SLIC Algorithm	21
13.	The Balls-and-Jacks Problem Using Youngs' Interface Reconstruction Algorithm Using Improperly Chosen Material Advection Orders	23
14.	The Balls-and-Jacks Problem Using SMYRA	24
15.	Example of a Deep Penetration Simulation in Which the Erosion Products of the Rod Come Into Contact With the Penetrator	25
16.	Comparison of a Deep Penetration Simulation With and Without the BLINT Model	27
17.	Comparison of Simulations Using the Different Strength Options in Mixed Cells	28

INTENTIONALLY LEFT BLANK.

List of Tables

Table		Page
1.	Sliding Interface Approach in Lagrangian Systems	6
2.	Computational Procedure for Sliding Interfaces	6

INTENTIONALLY LEFT BLANK.

1. Introduction

In companion papers [1, 2], sources of error in calculations involving fast, transient loading due to various meshing options available in commercial wave propagation codes, the use of constitutive models, and use of data at strain rates inappropriate to the problem are discussed. In this report, the effects of contact-impact algorithms in Lagrangian codes and the presence of material interfaces in Eulerian codes are discussed. Attention is limited to conventional production Lagrangian and Eulerian hydrocodes that are readily available in industry and government research centers. Arbitrary Lagrangian Eulerian (ALE) codes and meshless methods (such as the free Lagrangian or the smooth particle hydrodynamics [SPH] technique) are not covered here.

The ability to treat problems where adjacent components may independently slide, separate, and impact along free surfaces and material interfaces is crucial in many technical fields. The nuclear industry analyzes the impact of shipping casks containing radioactive materials, pipe-to-pipe impacts, and soil-structure interaction problems. Crashworthiness of vehicles is another important area, as is foreign-object-impact damage in aircraft. Erosion and failure of materials of high-speed aircraft flying through rain and hail is still a significant problem. Contact impact and sliding with and without friction is as important in metal forming as it is in biomechanics. In weapons design, relevant problems include the structural response of gun-fired projectiles, various bomb configurations, and a variety of shaped charge designs.

Spatial discretization using either finite-difference or finite-element techniques can be carried out in a Lagrangian or Eulerian framework (Figure 1). In a Lagrangian framework, the grid is embedded in the material and distorts with it so that the computation tracks the motion of elements of mass. In the Eulerian approach, the grid is fixed in space and material flows through it. Eulerian codes work well for situations where large distortions are encountered, such as in hypervelocity impact. There are advantages and disadvantages to both approaches. Lagrangian codes are conceptually straightforward. Since the grid distorts with the material, time histories are easily obtained and material interfaces are sharply defined. However, considerable mesh distortion,

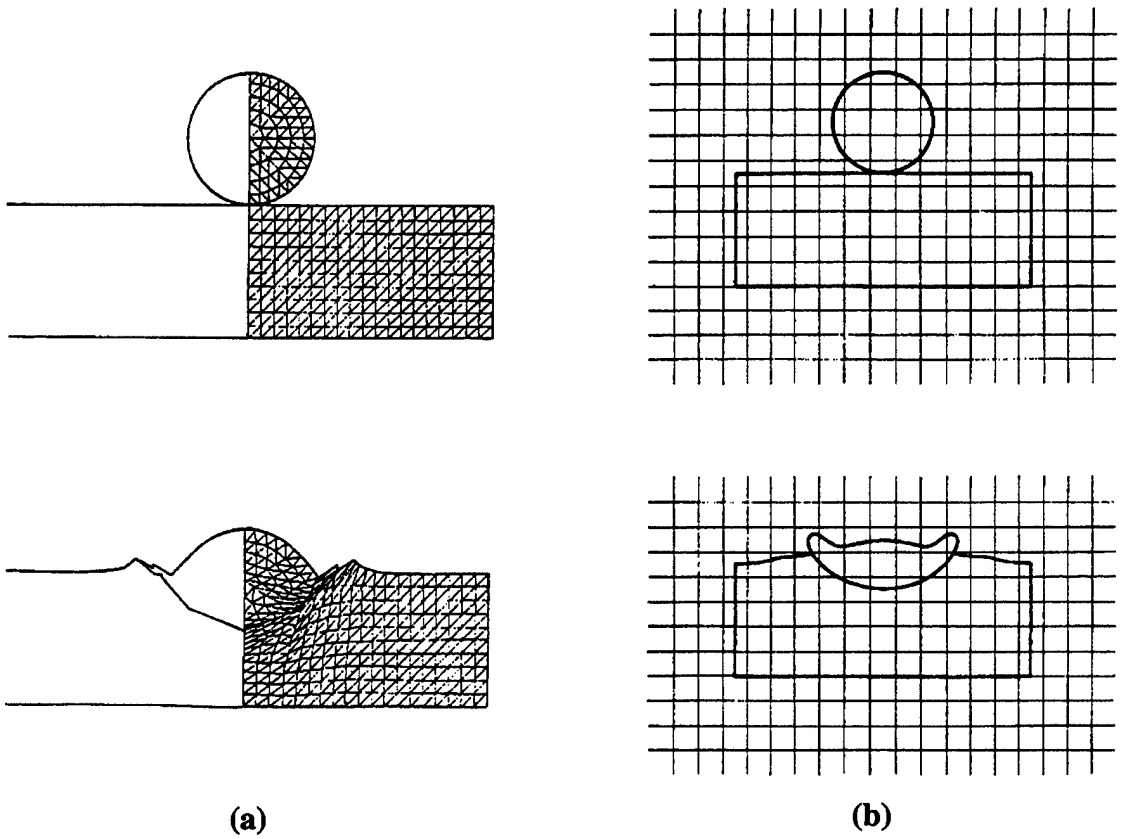


Figure 1. (a) Lagrangian Computational Grid and (b) Eulerian Computational Grid.

entanglement, and nodal intrusions across slide lines can occur and special logic is required for modeling deep penetration problems. In Eulerian codes, material is transported from cell to cell in the fixed grid. Considerable diffusion can occur, and special logic is required if interfaces are to be defined with greater precision than one or two cell dimensions. Additional information can be found in Zukas et al. [3], Zukas [4], Walters and Zukas [5], Hallquist et al. [6], Belytschko and Hughes [7], Schwer et al. [8], and Kulak and Schwer [9].

2. Lagrangian Calculations: Influence of Contact Surfaces on Solutions

Figure 2 [10] shows a typical interface setup between two contacting bodies, one side designated as master, the other as slave. Sliding-interface algorithms can be divided into three broad categories:

(1) the penalty method, or restoring force approach, particularly popular in structural dynamics and low-velocity applications, where nodal intrusions are corrected over several computational cycles;
(2) the "put-back" logic approach used in most hydrocodes, with or without erosion algorithms, where intruding nodes are repositioned on the contact surface in a single computational cycle; and
(3) novel approaches, such as the pinball algorithm [11].

In addition to these, there have been various ad hoc approaches used for specific problems. Each of these has proven useful in a specific spectrum of nodal (therefore impact) velocities, but none is sufficiently general to work in all applications from elastic impact through hypervelocity impact, where perforations occur and large debris clouds are formed.

At the outset of a Lagrangian calculation, where interpenetration of two or more bodies can be expected, the surface nodes likely to make contact are designated as slave nodes on one of the bodies and master nodes on another. With modern contact-impact algorithms, the designation is more or less arbitrary. These master and slave nodes must be designated by the code user. Codes such as

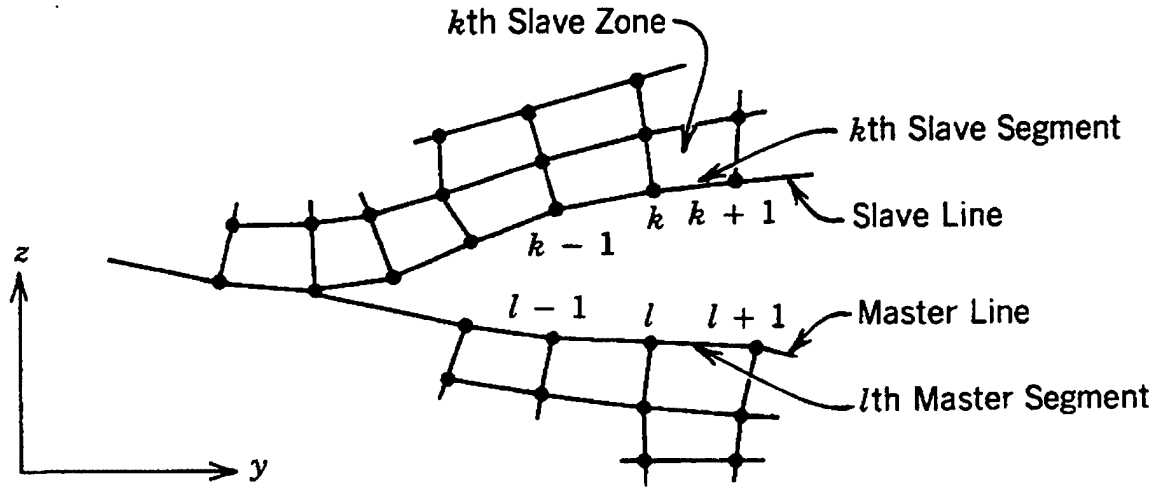


Figure 2. Typical Lagrangian Contact Interface Showing Master- and Slave-Node Designations [10].

ZeuS [12] eliminate this nuisance by automatically designating all geometric boundaries and material interfaces as contact surfaces. The user can remove them if they are not needed but is never required to specify them. The goal of sliding interface logic (also known as "contact-impact algorithms") is to prevent intrusion of a slave node through a master surface. Intrusions must be corrected. The procedures are outlined in Tables 1 and 2.

The most comprehensive contact algorithms of this sort are in the DYSMAS-L code [13]. Following the scientific method to its logical end, the authors of the code exhaustively considered every possibility of slide-line intrusion and programmed against it. Because all potential types of intrusion are checked, considerable time is expended in DYSMAS-L's contact processor at each cycle, making for a slow-running code, but one without any significant errors due to the contact processor. In the United States, the approach in codes such as DYNA [14, 15], EPIC [16, 17], PRONTO [18], ZeuS, and others has been more pragmatic. These guard against the major sources of error that are likely to occur. Once intrusion of the master surface is detected, the offending node is repositioned in one or another fashion and contact conditions and momentum balance are enforced locally on the sliding interface. Pathological cases are then treated as they occur.

By constrast, with penalty methods, the restoring force on an intruded slave node is very sensitive to the stiffness coefficient, which, for quite some time in the history of Lagrangian code development, was a user-defined parameter and a rather significant source of error if the code user was not familiar with the physical problem and his/her code. The current practice is to determine the restoring force modulus from the properties and geometry of the element hosting the sliding segment. Prior to this, results could be dramatically affected by a poor choice of stiffness constant and that choice was very much a matter of experience. By way of example, Goudreau and Hallquist [19] incorporated procedures in NIKE and DYNA3D to compute a unique modulus for each slave and master segment based on the thickness and bulk modulus of the element in which it resides. They state that "... in our opinion, the lack of user control over this very critical parameter greatly increases the success of the method."

Table 1. Sliding Interface Approach in Lagrangian Systems

Designate master and slave material.
Decompose $\dot{u}$, $\ddot{u}$ into normal and tangential components.
In normal direction: -motion coupled during contact, and -independent when separated.
In tangential direction: -independent when materials separated or interface frictionless, and -modified when there is contact or frictional force acts.
Tied sliding - maintain displacement compatibility at abrupt grid changes.

Table 2. Computational Procedure for Sliding Interfaces

(1) Identify a series of nodes that make up the master surface.
(2) Identify a series of nodes that make up the slave surface.
(3) For each Δt, apply equations of motion to both master and slave nodes.
(4) Check for interference between slave nodes and master surface: -define search region, -check each slave node not on master surface, and -if penetration occurs, move slave node to master surface.
(5) Once slave nodes are moved onto master surface: -invoke momentum balance, -apply frictional forces, and -open voids (if tensile forces present).
(6) Repeat (3)–(5) for each Δt

While this restorative procedure of the penalty method gave a smoothness to the calculation due to the fact that restoration of intruding nodes, and therefore element volume changes, was gradual, the procedure did not lend itself to impacts at ordnance velocity or hypervelocity because intrusions could exceed element dimensions. Hence, most existing Lagrangian hydrocodes use the put-back logic mentioned previously. The intruding node or nodes are put back onto the master surface in one time step, and momentum balance is invoked. Efficient search procedures for slave-node intrusion are required since a Lagrangian code is made or broken by the accuracy and efficiency of its contact logic.

Ideally, the operation of the contact processor should be transparent to the user. Very much, however, depends on the gridding in the vicinity of the contact surface and the local time step. Breidenbach et al. [20] provide a comprehensive discussion of pathological cases that can arise with slide-line logic. Grove et al. [21], studying tungsten projectiles penetrating titanium targets, exercised the various erosion options in EPIC (upon failure of an element, its connectivity is no longer considered and the nodal masses associated with that element can be retained in the calculation or ignored) and compared results using the data for the Johnson-Cook models [22, 23] in the EPIC materials library with results using strength data reported by Burkins et al. [24]. Results for one of the calculation sets are shown in Figure 3. The differences between the calculation sets are due to a combination of data for the selected constitutive model and the behavior of the sliding interface logic when dealing with free-flying masses.

The Lagrangian codes, which first appeared in the early 1960s, such as HEMP and TOODY, had no means of dealing with the large distortions that can occur under impact and explosive loading. They required that the contact surface, or sliding interface, specified at the beginning of a calculation remain unchanged. In effect, an impenetrable membrane was placed over and attached to the colliding bodies. Thus, colliding bodies could not fail but could distort ad infinitum. A dramatic example of such distortions is shown in Figure 4 [25]. Thus, these codes were limited to the study of the early stages of impact phenomena. In order to extend the capability of these codes, rezoning techniques were invented. In rezoning, a new Lagrangian computational mesh is overlaid on the distorted mesh. A rezone algorithm maps mesh quantities of the severely distorted mesh onto the

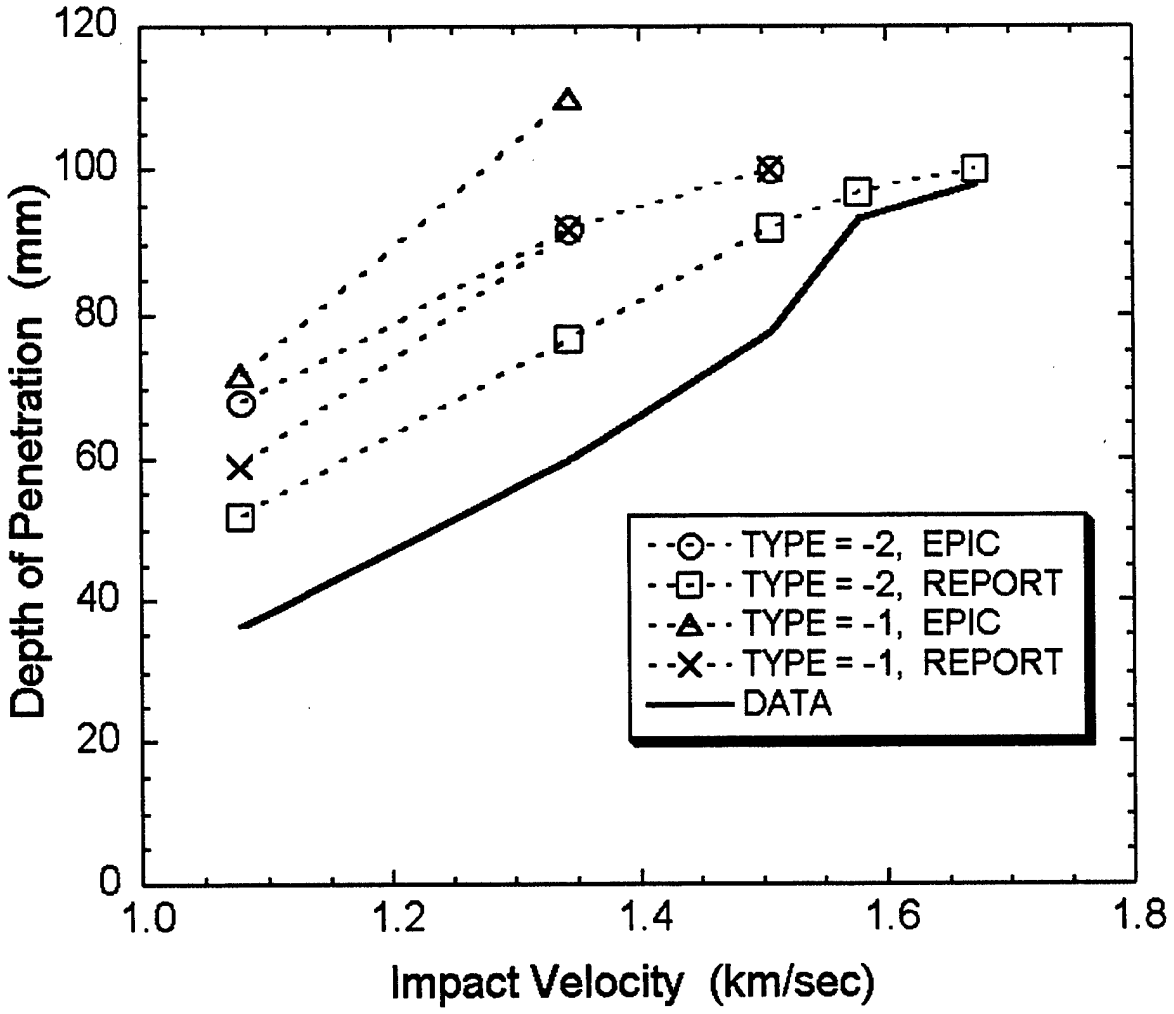


Figure 3. Comparison of Eroding Slide-Line Options on Numerical Results for a Deep-Penetration Problem. The Type = −1 Option Retains the Mass of the Eroded Elements at the Nodes, While the Type = −2 Option Discards Mass Once an Element Erodes. Also Compared Are Simulations With Strength Data Taken From the EPIC Library to Simulations Using Strength Data Reported Elsewhere. The Solid Line Represents the Experimentally Obtained Data [21].

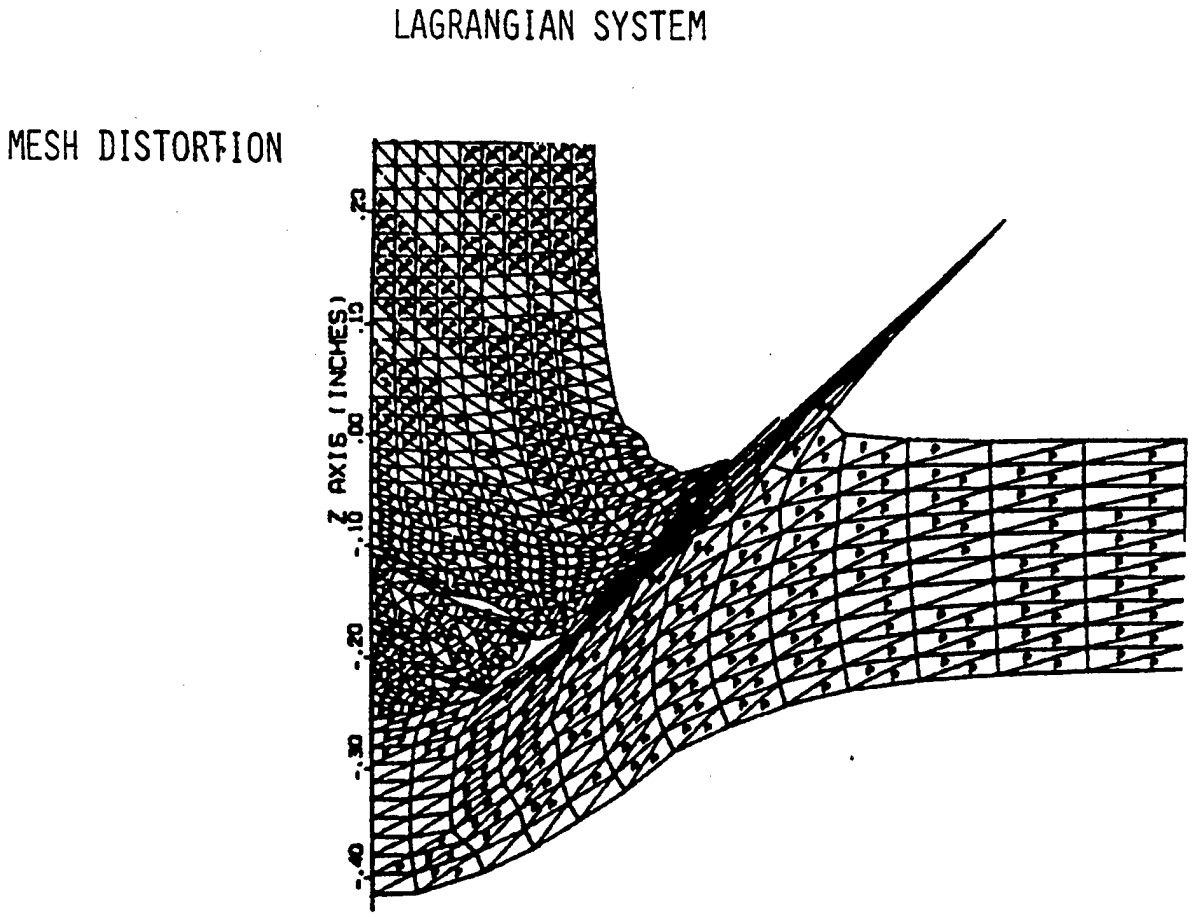
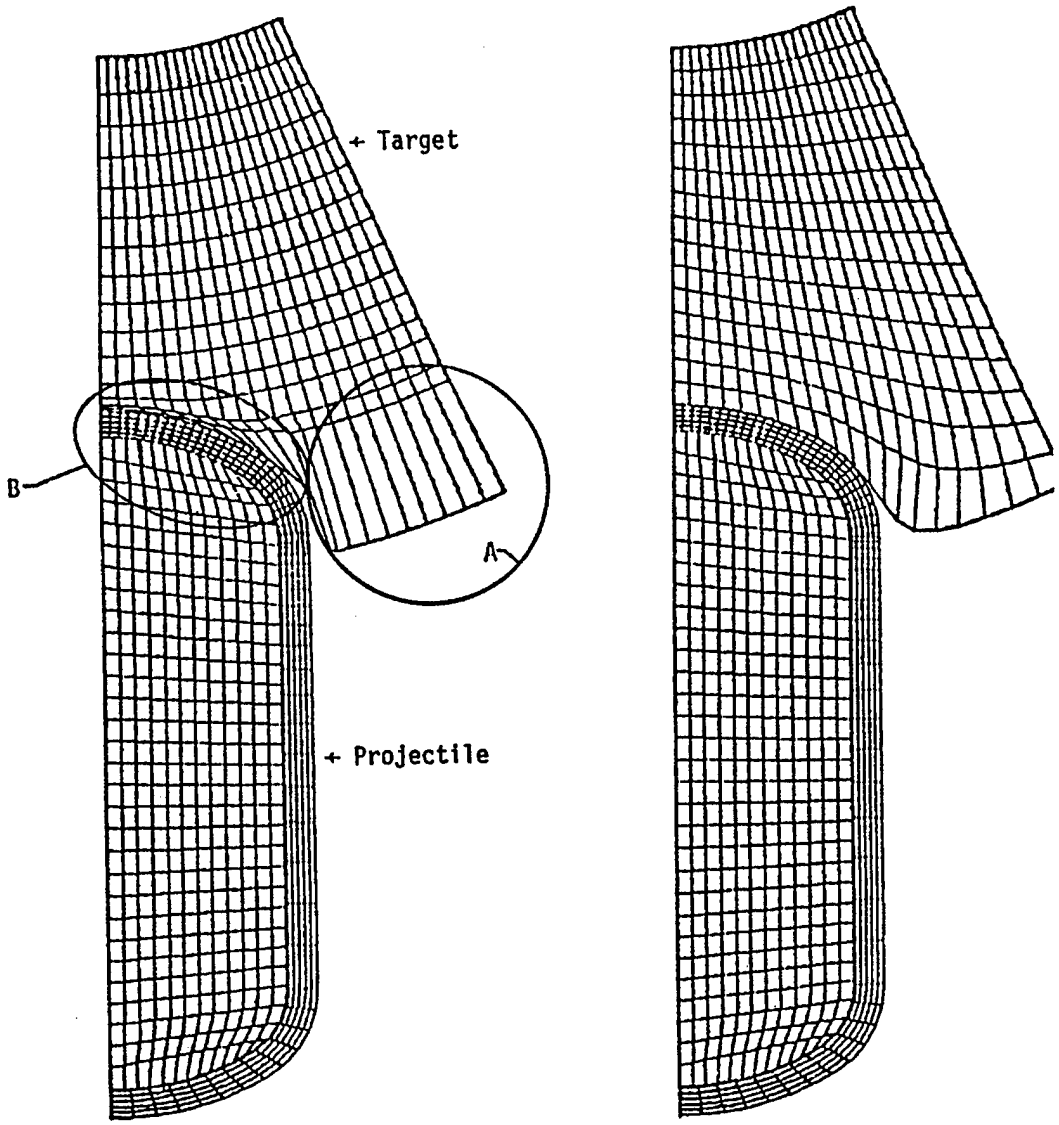


Figure 4. Example of Extreme Distortion in a Lagrangian Calculation [25].

new mesh such that conservation of mass, momentum, total energy, and the constitutive relationship are satisfied. Rezoning was, and remains, a nontrivial process. For deep penetration problems, 30 to 50 rezones are not uncommon. Since, at each rezone, the accumulated history of several elements is combined into a larger element, frequent rezoning renders the computational mesh semi-Eulerian in that large distortions are realized but material history and location of material boundaries are diffused. Indeed, if rezoning were to take place at each cycle, the computations could be effectively Eulerian. Frequent rezoning gives computational results a smoothness characteristic of Eulerian calculations. Many codes today, such as DYNA, incorporate automatic rezoners. Despite the label, they still require occasional human intervention. This suggests that, despite good intentions, rezoned calculations can be made to mirror the expectations of the user monitoring the process. An example of a rezoned calculation is shown in Figure 5 [26].

The eroding slide-line concept proved to be a major breakthrough in extending the capabilities of Lagrangian codes to do problems involving deep penetration or multiple-plate targets and other situations where damage is highly localized. The term "erosion" in this context does not refer to a physical failure mechanism. Rather, it describes bookkeeping procedures that allow dynamic redefinition of master and slave surfaces when very large distortions occur. The overall result makes it appear that the colliding bodies are "eroding." Some examples of the success achieved with this technique are shown in Figures 6–8. Figure 6, taken from Kimsey and Zukas [27], shows the computational grid overlaid on the recovered target from the impact of a long steel rod onto a semi-infinite armor steel target at a velocity of 3.114 km/s. Figure 7 [28] shows debris-cloud formation, propagation, and interaction with other components of a space vehicle. Figure 8 [29] shows the penetration of a 50-ply aluminum plate by a steel projectile 15 μs after impact.

Eroding slide-line techniques are available in virtually all Lagrangian hydrocodes today. The name of the procedure may change (e.g., "advected elements" is popular today), but the procedure is essentially as described previously. While very useful, such techniques should be used with caution. Energy is not conserved in most sliding-interface prescriptions. The total energy in each calculation should therefore be carefully monitored. Losses of 4–10% in contact calculations can be tolerated for most high-velocity impact problems. Anything greater than 10% is usually



(a) Mesh Before Rezoning

(b) Mesh After Rezoning

Figure 5. Lagrangian Calculation Before and After Rezoning [26].

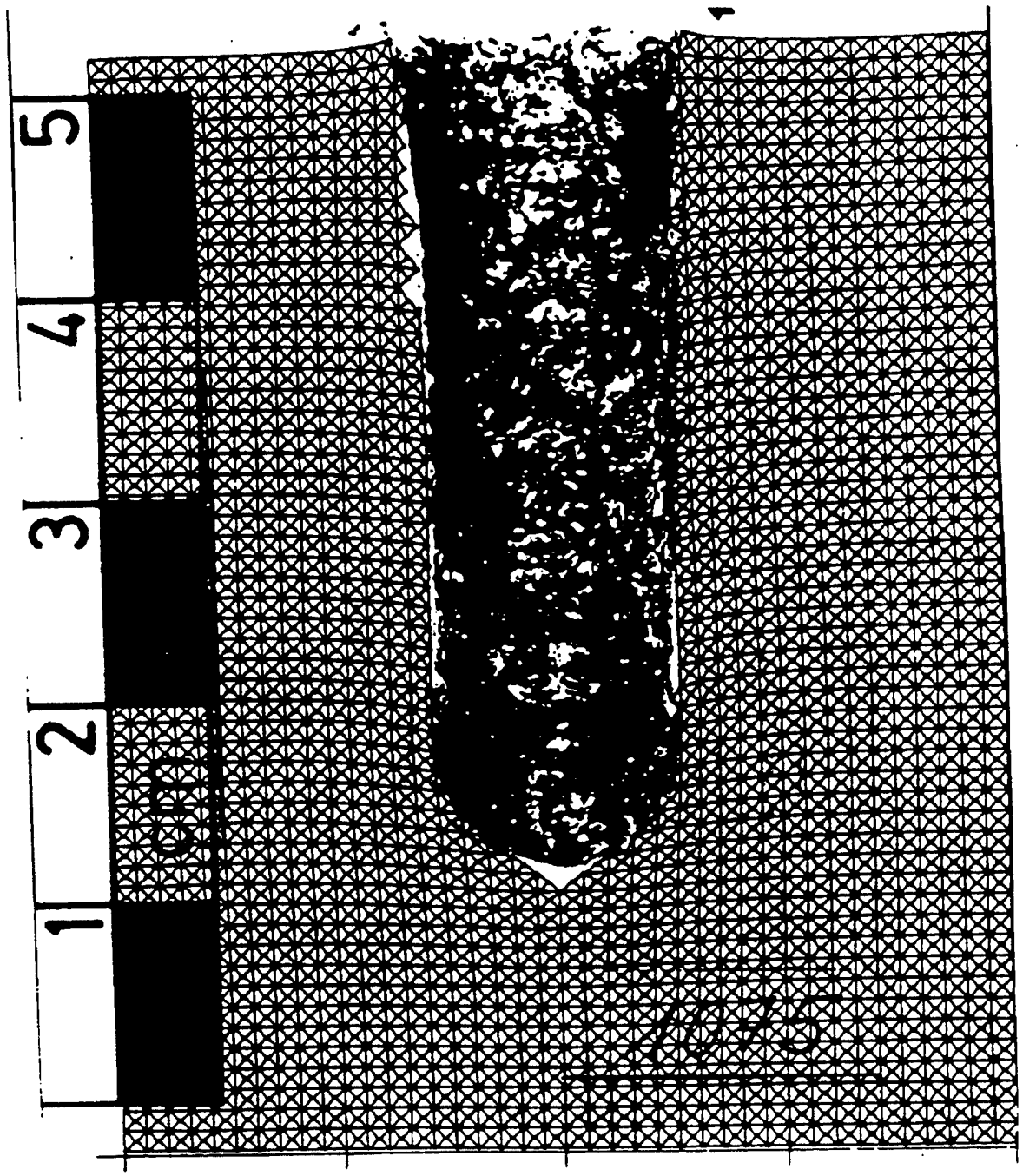


Figure 6. Overlay of Computed and Experimental Hole Profiles for Steel-Steel Penetration, V_s = 3.114 km/s [27].

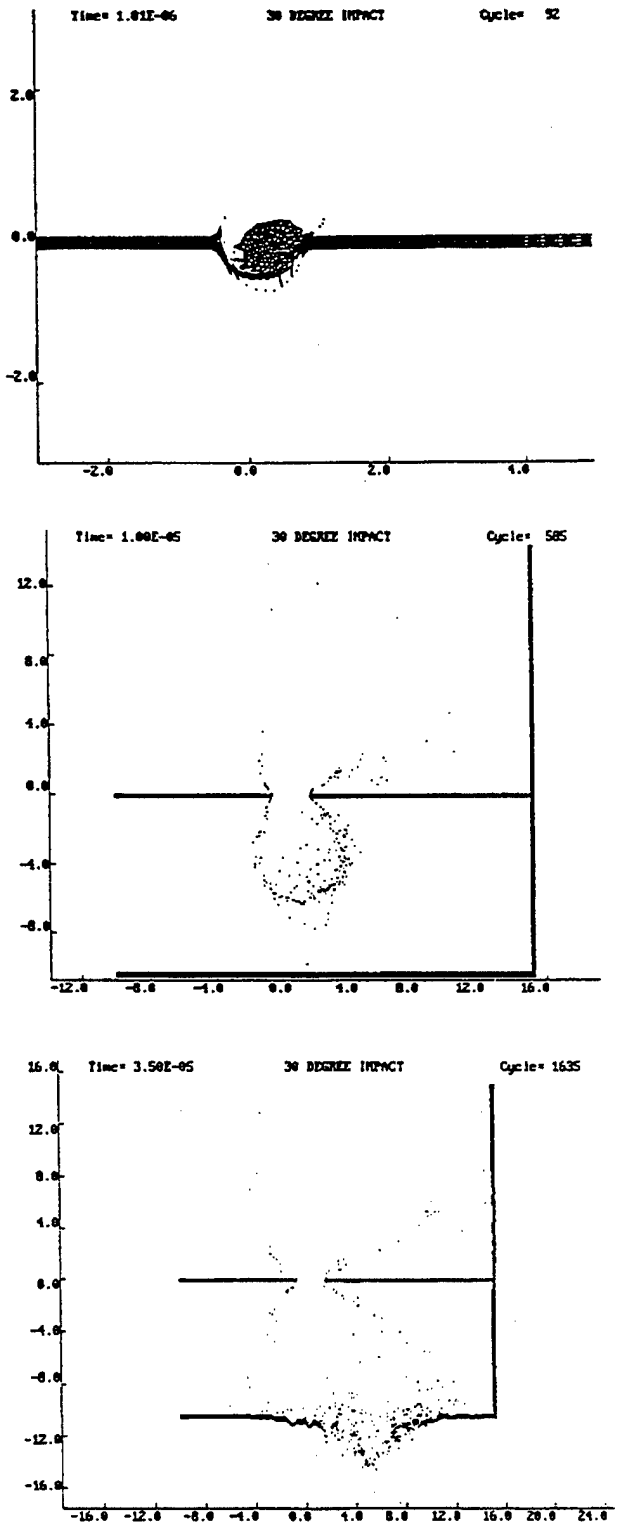


Figure 7. Damage Due to Sphere Impact at 30° [28].

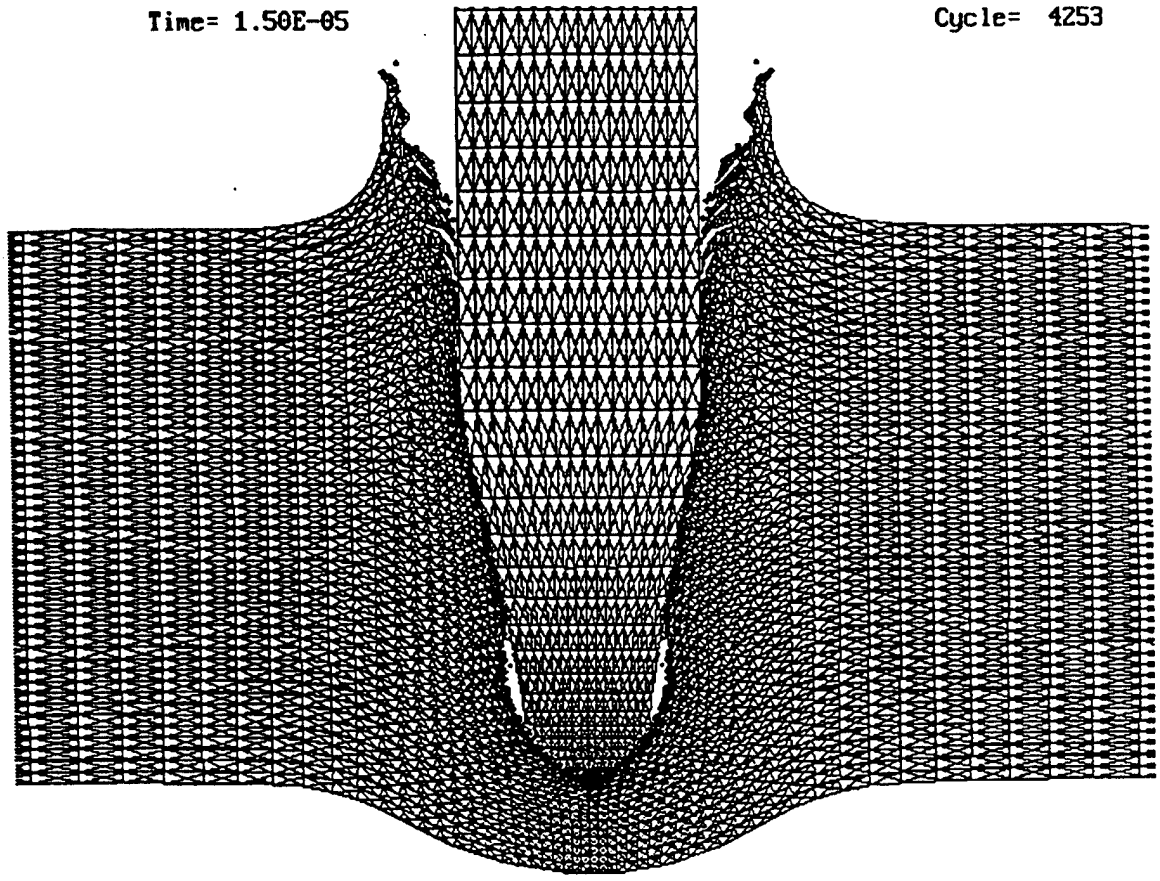


Figure 8. Penetration of a 50-Ply Aluminum Target 15 μs After Impact [29].

indicative of a serious problem and should prompt a check of both the computational model and the data used for the constitutive models.

In penetration problems, a situation often encountered is the continuation of penetration after the projectile has eroded. This is shown in Figures 9 and 10. So many nodes accumulate at the centerline element of the target (close to 180 nodes in this case) that the element can no longer withstand the impacts and fails. As it fails, more nodes fall into the crater and the target appears to unzip along its centerline. Above this artificial crack, the crater dimensions and penetration depth are about as expected. The cause for this behavior is unknown at present, but clues to the problem may be found in the work of Brach [30] and Walsh [31]. Hydrocodes are formulated assuming continuum behavior. The impact of single or multiple mass points against an intact element may violate that assumption. Brach gives computational procedures for discrete particle impacts against continuum structures. Walsh studies the effects of the impact of minuscule mass points against continuum targets and found that the apparent strength of the target increased by a factor of 4.7 over pretest-measured strength properties. The formulation of the slide-line algorithm may also be a factor. Introducing an analytical formulation for the contact processor in version 4.23 of ZeuS (the calculations shown here are with the standard version 4.22) helped to considerably reduce the unzipping effect.

3. Eulerian Calculations: Effects of Material Interface on Solutions

In Lagrangian codes, the mesh moves with the material, whereas in Eulerian codes the materials flow though the mesh. This is typically done in two phases. In the first phase, the mesh is allowed to distort as the problem is advanced in time (the Lagrangian phase), and, in the second phase, the distorted mesh is remapped back to the original mesh (the advection phase). Operator splitting is typically employed during the advection phase such that the remapping occurs one coordinate direction at a time, and the order is reversed each cycle. For example, the order in which advection occurs may be in the x, y, then z directions one cycle and in reverse order the next. Similar to the contact algorithm in Lagrangian codes, the advection phase is the most computationally intensive

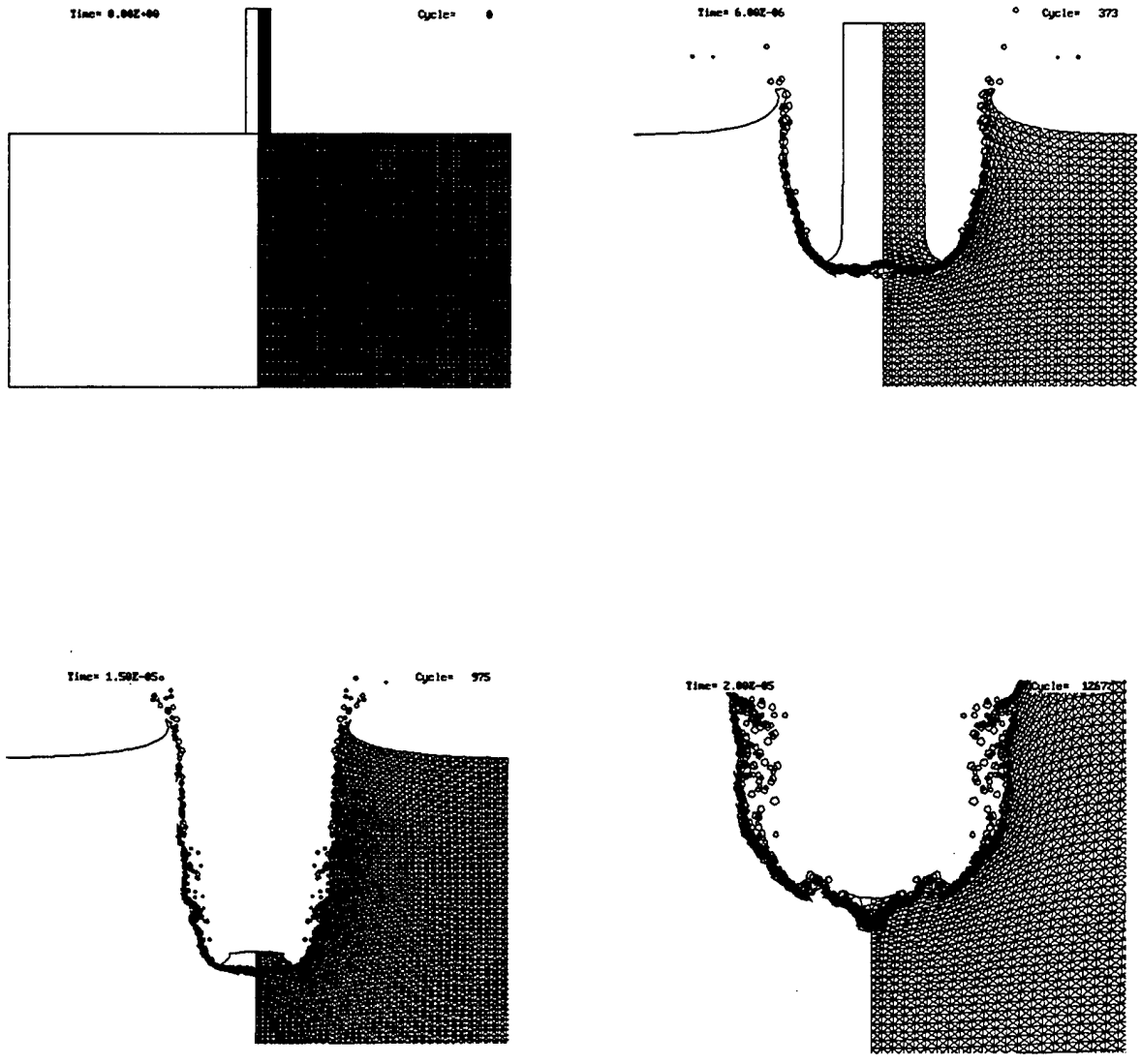


Figure 9. Penetration of an L/D = 5 Aluminum Rod Striking a Thick Aluminum Target at 6 km/s.

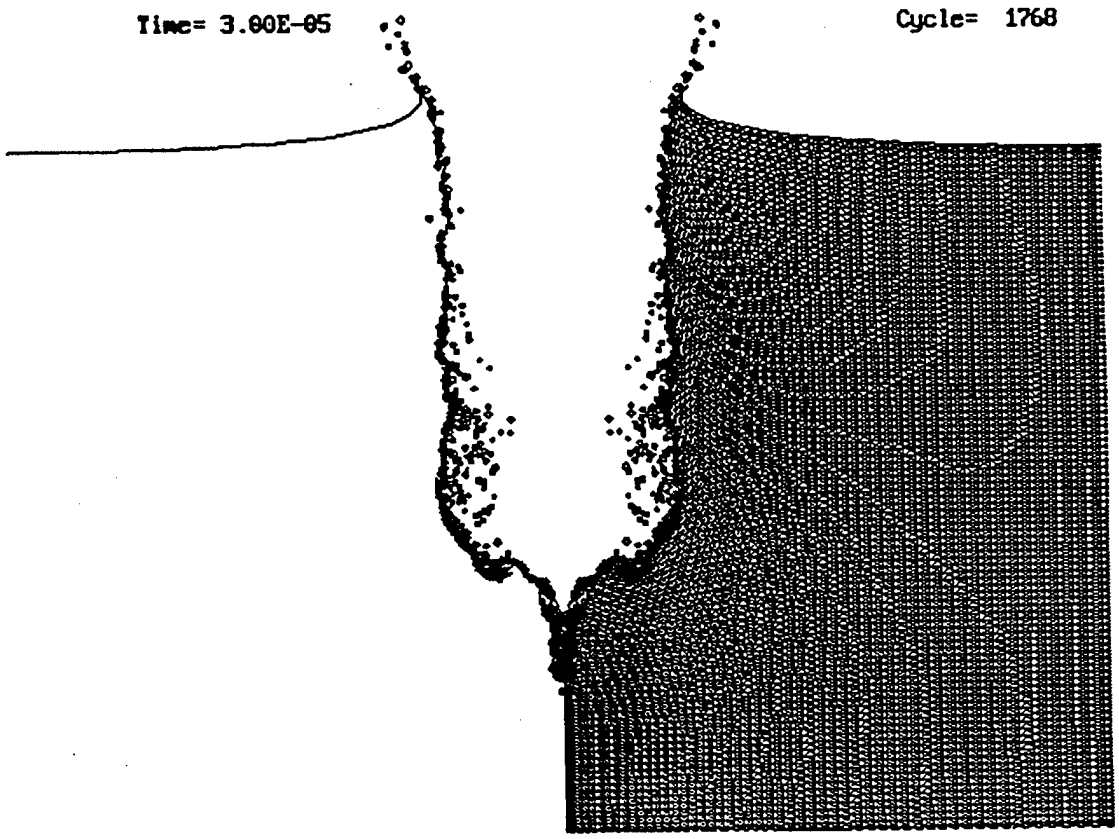


Figure 10. Residual Penetration by Eroded Mass Points.

in Eulerian codes. Some codes (such as MESA [32]) allow subcycling of the Lagrangian phase (i.e., allowing several Lagrangian phases before performing a single advection phase).

As is shown in Figure 1(b), material interfaces are not well defined in Eulerian codes. The interface between two dissimilar materials is known at best to within some fraction of a cell dimension. These interface cells contain materials of both the bodies involved in contact and are therefore designated as "mixed cells." Not knowing the location or orientation of an interface within a mixed cell is a serious drawback, and a number of techniques have been invented to overcome this problem.

The earliest attempt to refine the location of a material interface in an Eulerian calculation involved the use of massless Lagrangian tracer particles. A number of these would be introduced at the outset of the calculation, typically defining the boundaries of colliding objects. This required that both Lagrangian and Eulerian calculations be performed each cycle. The massless tracers were connected by straight lines. This approach worked initially, but problems arose as the distance between tracers increased with increasing deformation. Additional tracers would need to be introduced by the code user at various restart times to prevent materials from flowing across boundaries. In effect, this amounted to manually assisted rezoning in codes such as HELP [33]. As an example of this approach, a typical HELP code calculation is shown in Figure 11. While the addition of tracers alleviated the problem of boundary transgression, it also introduced a subtle error in the calculation. The placement of the tracers influenced the further computation of displacements so that, all too often, the final resultant deformation was a reflection of the preconception of the code user. If the user was inexperienced and unfamiliar with high-velocity impact physics, the errors introduced into the calculation could be quite far from subtle. In that era, there was a very small body of experienced computational analysts who performed such calculations. Novices tended to serve lengthy apprenticeships under experienced code users, many of whom had studied under code developers. Hence, despite slow computers and long computation times, results tended to be quite good.

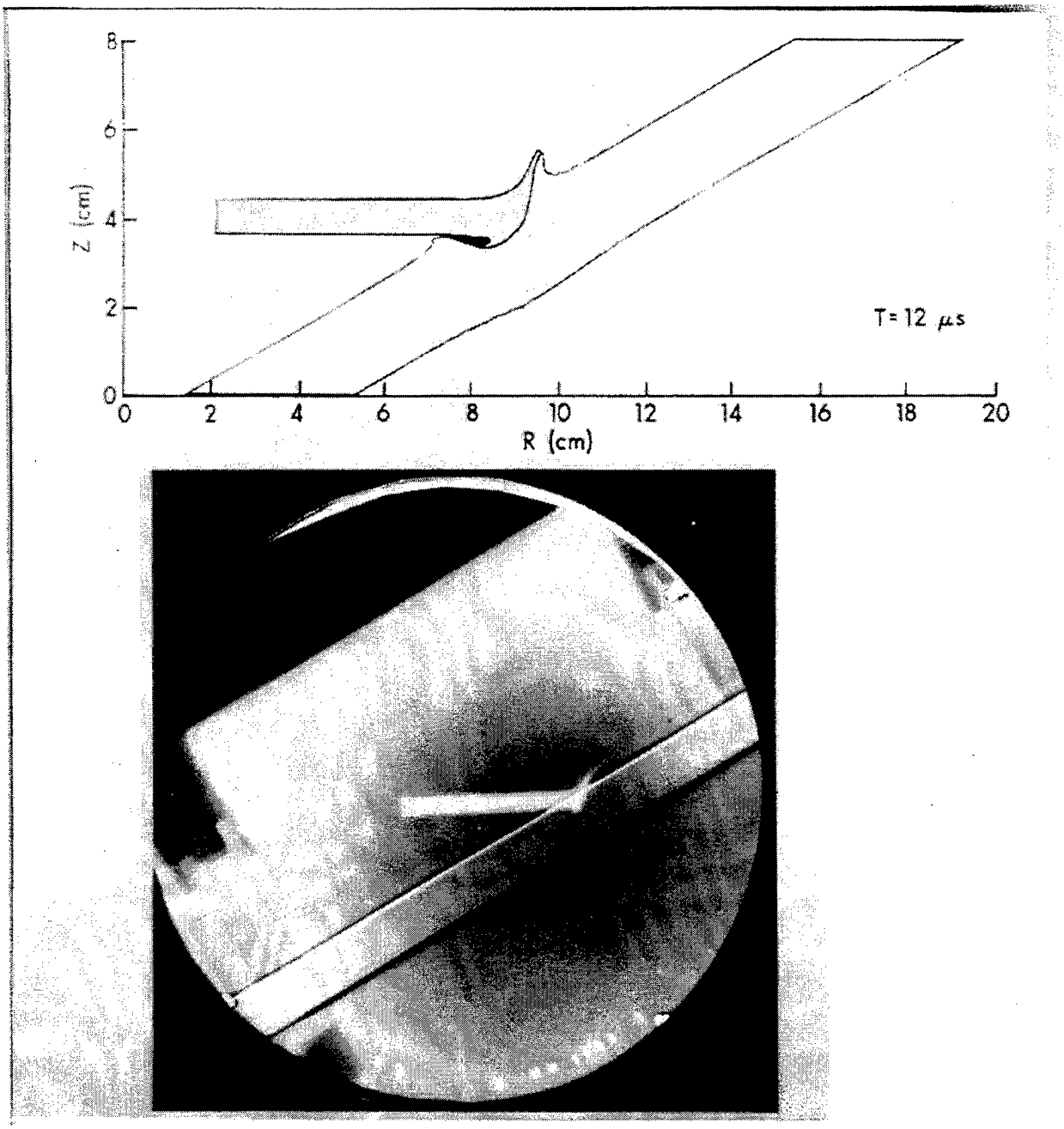
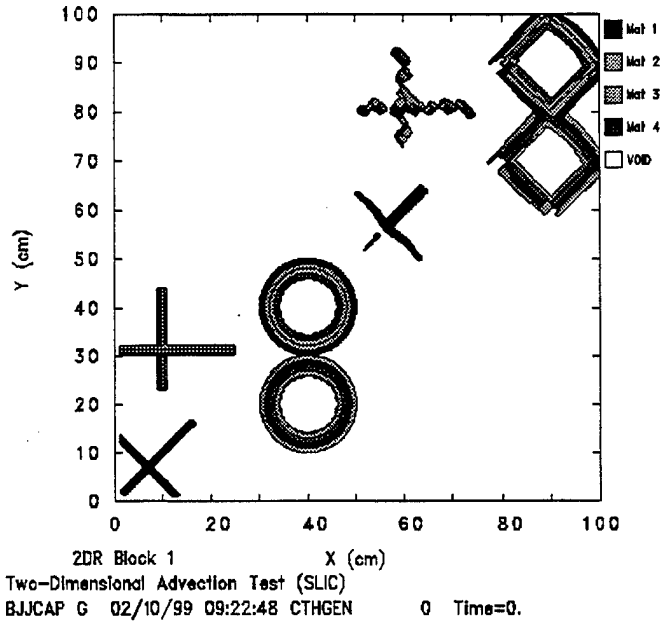


Figure 11. A Typical Plane-Strain HELP Code Simulation Compared With Experiment.

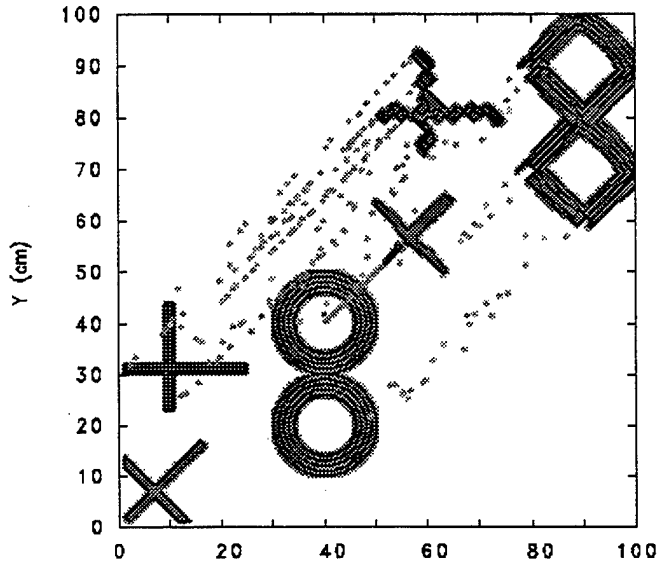
Considerable improvements in the use of Lagrangian particles to define interfaces were made in the SMITE code [34–37]. In SMITE, a second-order Eulerian finite-difference code, each material had its own independent grid. Thus, the mesh spacing and number of mesh grids in one material is not affected by any other material. The extent of each domain was determined by particles that defined the domain boundary. These points were moved in a Lagrangian sense by integrating the ordinary differential equations relating their positions or velocities. Additional particles were added as needed to ensure uniform spacing throughout the calculation. The interaction between materials was through the boundaries. The boundary points were subject to free-surface and interface conditions and provided the only communication between the various material domains.

The next step in complexity, if not necessarily accuracy, involves the use of interface reconstruction algorithms. One of the most successful (because of its simplicity) material interface reconstruction algorithms was the first-order accurate simple line interface calculation (SLIC) algorithm of Noh and Woodward [38]. The algorithm treats each coordinate direction independently and represents material interfaces as straight lines either perpendicular or parallel to a coordinate direction based on the volume fractions of neighboring cells. The order in which each coordinate direction is treated is reversed each computational cycle. The SLIC algorithm did well when material flow was primarily in a coordinate direction but tended to reorient the material interfaces if material flow was not parallel to a coordinate direction. For example, SLIC would tend to reorient the material interfaces of a circle moving the mesh at 45° such that it would take on a diamond shape. An example of the algorithm is provided in the "balls-and-jacks" problem shown in Figure 12 in which two balls (resembling a "figure eight") and two jacks are moved through the mesh at 45° with x and y velocity components of 100 km/s.

Most modern production Eulerian hydrocodes use a second-order-accurate material interface reconstruction scheme. One such scheme is Youngs' interface reconstruction algorithm [39]. The Youngs' algorithm also uses lines (or planes in three dimensions) to represent the material interfaces; however, the lines can be at any angle. A problem with the Youngs' algorithm is that the code user is required to input the order in which materials will advect. The wrong choice of material advection



(a)



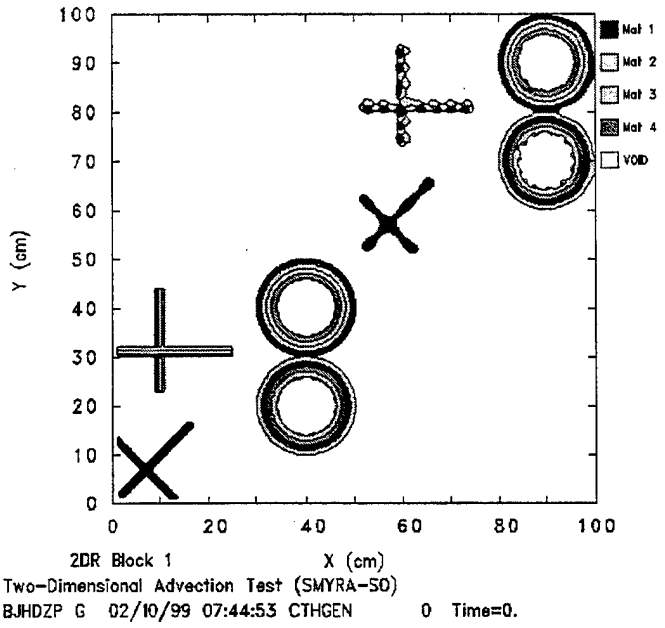
(b)

Figure 12. The Balls-and-Jacks Problem Using the SLIC Algorithm. (a) Material Interface Plot Shows the Initial and Final Configurations of the Balls and Jacks. The Interfaces Are Reoriented in the Direction of Motion. (b) Material Volume Fraction Plot Shows That Small Fragments of Material Are Left Behind.

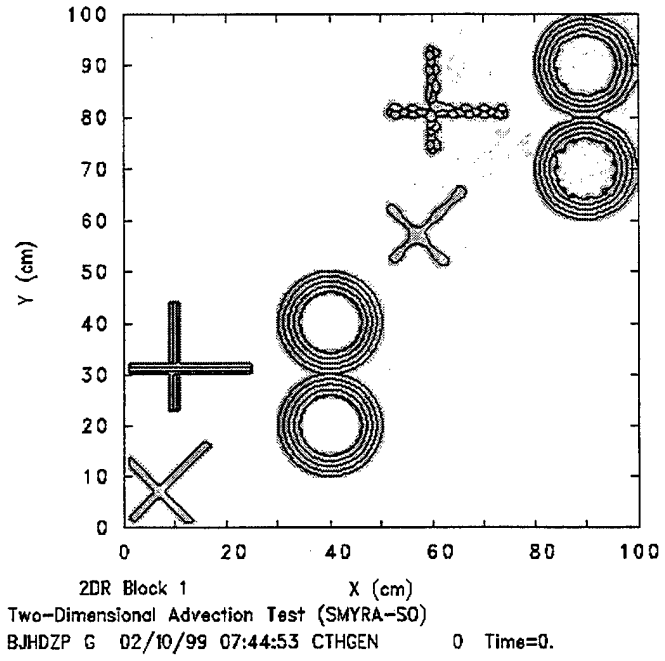
order can lead to strange results, as shown in the balls-and-jacks problem in Figure 13. In very complex problems involving many materials, considerable skill is needed in choosing the material advection order. Additionally, the advection order of materials in a complex problem is rarely uniform over the entire computational domain. The problems with the choice of material advection order were largely solved with the Sandia modified Youngs' reconstruction algorithm (SMYRA) [40] used in the CTH code [41], which is essentially Youngs' algorithm, but material volume fractions of neighboring cells are used to determine the advection order in mixed cells. An example of the balls-and-jacks problem using SMYRA is shown in Figure 14. A more comprehensive review of material reconstruction algorithms can be found in the work by Benson [42].

Even with a perfect material reconstruction algorithm, problems can occur when objects with the same material identity come into contact. The interface in this case will simply disappear, and the material behaves as though it were bonded together. This occurs because material interfaces can only be determined between different materials or materials and void, not like materials (meaning materials that are assigned the same material number). An example is shown in Figure 15 for a deep penetration problem involving a tungsten alloy projectile penetrating a steel target. In this case, the erosion products of the long-rod penetrator came in contact with the penetrator and the interface between the penetrator and erosion products can no longer be distinguished. The end result was that the simulation underpredicted final penetration due to the penetrator being decelerated from the contact.

Velocities in most Eulerian hydrocodes are either face centered or node centered, while other cell quantities are cell centered. Therefore, materials in a mixed cell all have the same velocity field. Thus, a cell moves as a distorting block implying a no-slip condition. Therefore, Eulerian codes do not handle problems very well where sliding between materials occurs or where materials separate. Unfortunately, sliding occurs in most problems. Attempts have been made to correct this shortcoming. For example, Silling [43] developed a boundary layer algorithm for sliding interfaces (BLINT) for two-dimensional problems. The algorithm creates a "slip layer" in a user-defined "soft" material. The strength of the cells in the slip layer is set to zero, allowing sliding to occur outside of the mixed cells. The model has been used with some success in modeling

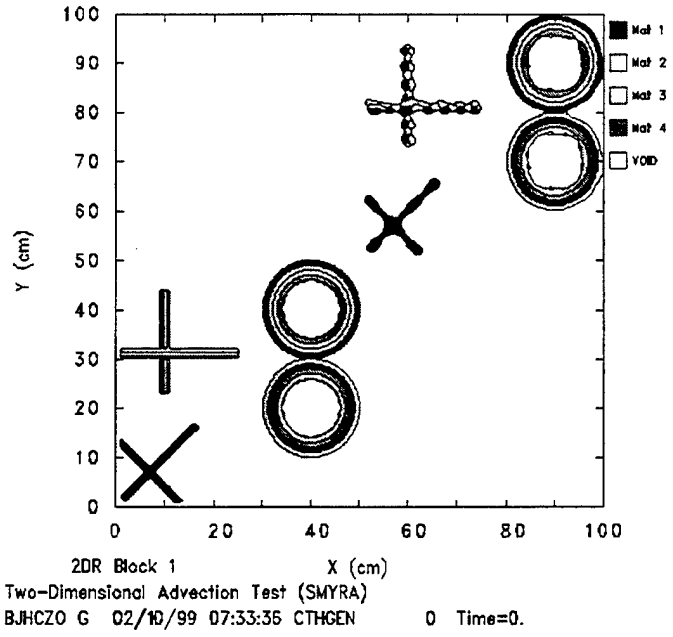


(a)

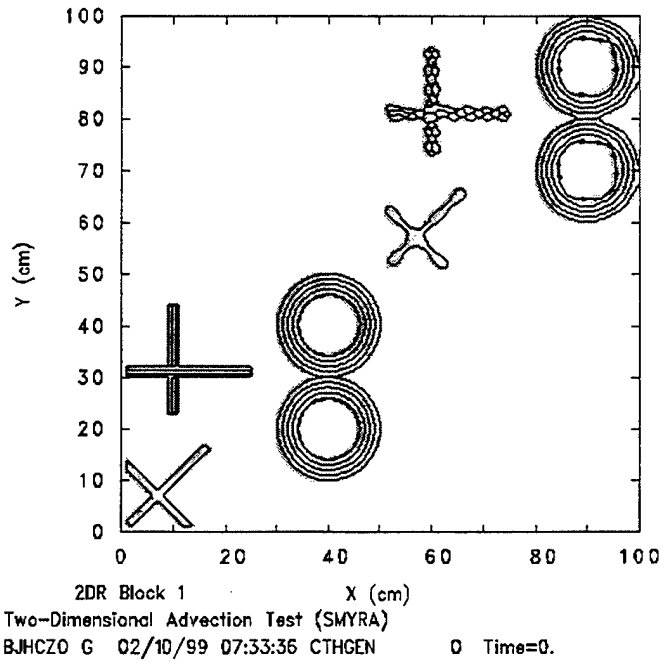


(b)

Figure 13. The Balls-and-Jacks Problem Using Youngs' Interface Reconstruction Algorithm Using Improperly Chosen Material Advection Orders. (a) Material Interface Plot Shows That the Algorithm Does a Better Job Keeping Track of the Material Interfaces Than the SLIC Algorithm of Figure 12(a). (b) Material Volume Fraction Plot Reveals That Material Incorrectly Advected Is Being Left Behind.



(a)



(b)

Figure 14. The Balls-and-Jacks Problem Using SMYRA. (a) Material Interface Plot Shows Results Similar to the Youngs' Algorithm of Figure 13(a). (b) Material Volume Fraction Plot Reveals That No Material Fragments Are Being Left Behind.

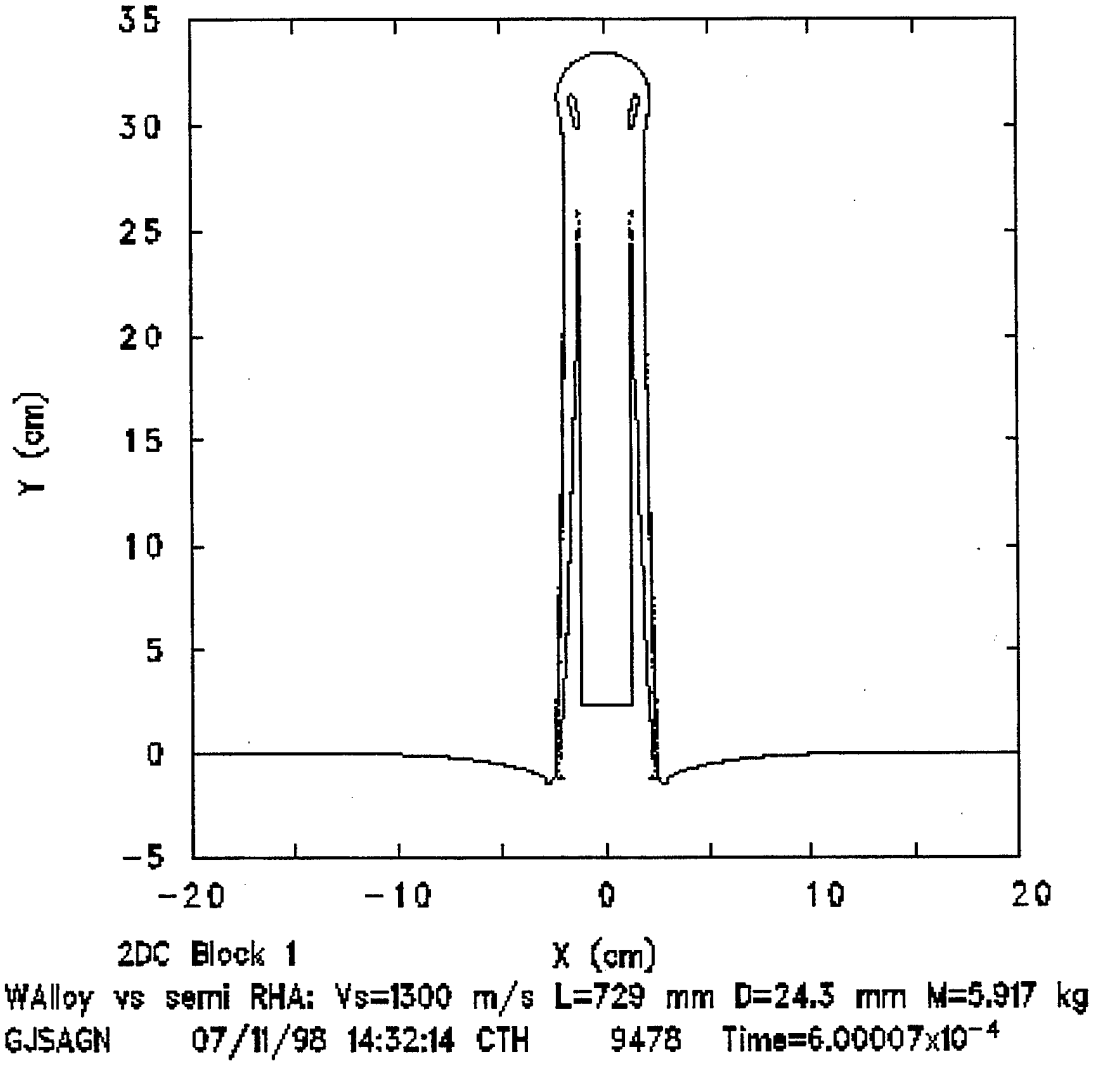
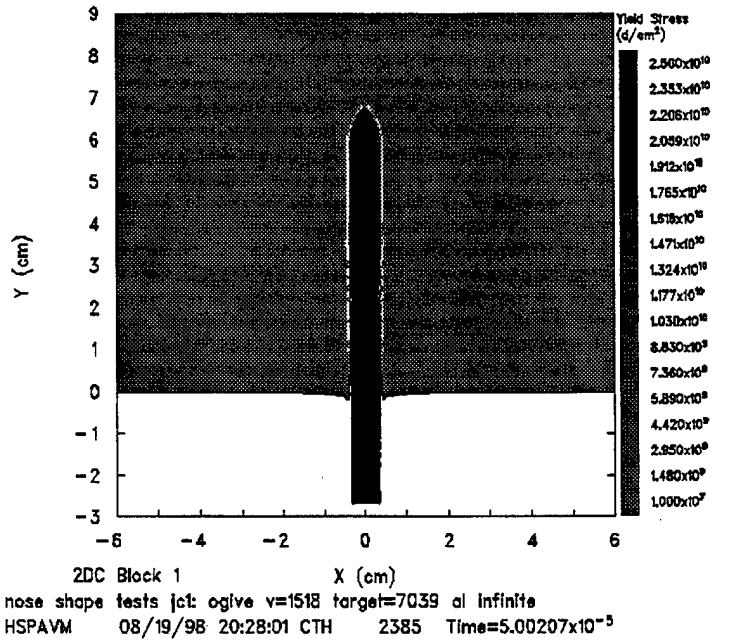


Figure 15. Example of a Deep Penetration Simulation in Which the Erosion Products of the Rod Come Into Contact With the Penetrator. At the Point of Contact, an Interface Is Indistinguishable. The Contact Caused the Penetrator to Decelerate More Rapidly Than Usual, Causing the Simulation to Underpredict Penetration.

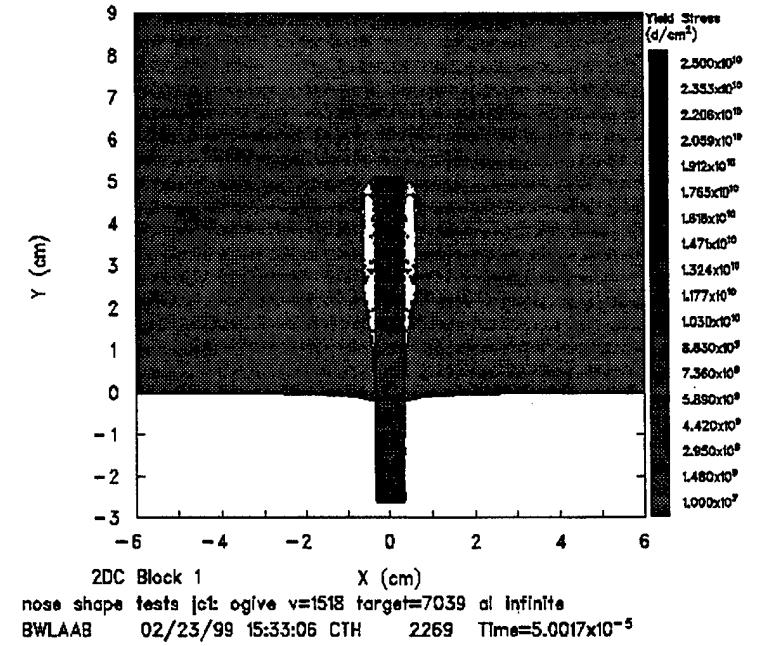
rigid-body penetrations [44–46] and has recently been extended to three dimensions. An example problem comparing simulations with and without the BLINT model is shown in Figure 16. Walker and Anderson [47] attempted to overcome the problem by developing a model for multimaterial velocities in mixed cells. The model defined a cell-centered velocity and allowed each material to have its own velocity, which was advected as a state variable. The model was strictly geometrical. The authors attempted to model a rigid-body penetrator problem using the model with only limited success.

Because the cell stress increments are calculated from velocity gradients, using the face-centered or node-centered velocities, a single yield strength must be calculated for mixed cells. Some Eulerian hydrocodes allow the user to select the formulation for determining the yield strength of a mixed cell. As an example, the CTH hydrocode gives the user three choices on how the yield strength of a mixed cell is determined. They include (1) setting the strength of a mixed cell to zero; (2) multiplying the yield strength of each material by its volume fraction and adding them; and (3) multiplying the yield strength of each material by its volume fraction, summing them and dividing by the total volume fraction of all materials within the cell. All these methods for determining the yield strength in a mixed cell can lead to calculating unrealistic results when the materials within a mixed cell have vastly different strengths. Figure 17 compares simulations using the previously mentioned strength treatments for mixed cells. For each strength formulation, the penetrator did not perforate the target, when, experimentally, it was determined it should. The reason is partly due to the strength treatment artificially weakening the penetrator material in mixed cells and partly due to the fracture model chosen. If a solid were in a mixed cell with a gas, the solid can undergo unrealistic deformation. The strength treatment used in mixed cells is one reason most Eulerian codes cannot model rigid-body penetration.

Mixed cells can also cause thermodynamic problems. This occurs because most Eulerian codes typically determine the thermodynamic state of the mixed cell on a subcell level. The thermodynamic state of neighboring cells is not used to determine the state of materials within a mixed cell. Assumptions must therefore be made to give a closed set of equations to determine the state within a mixed cell. The assumptions most often used include (1) all materials are at the same

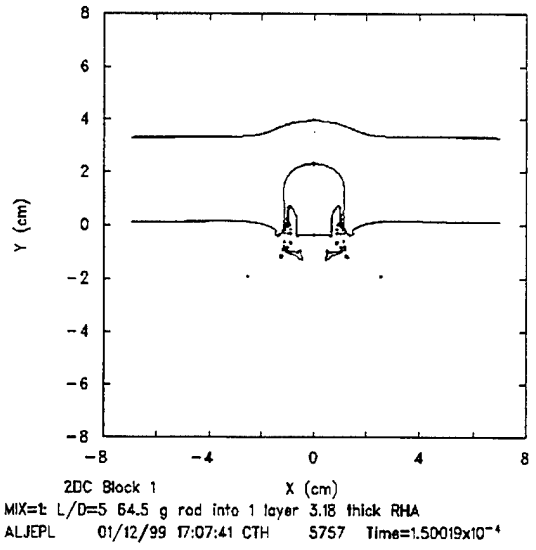


(a)

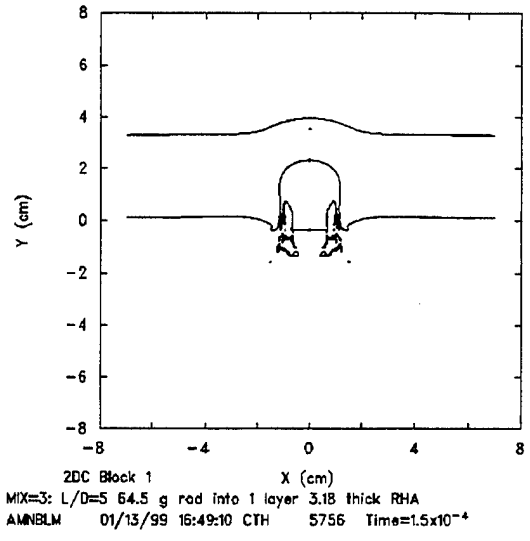


(b)

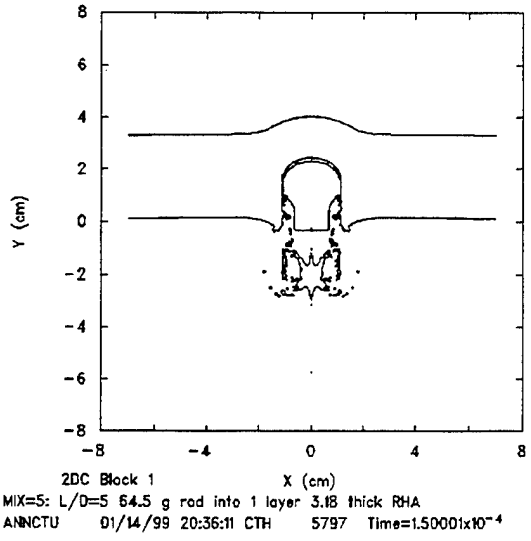
Figure 16. Comparison of a Deep Penetration Simulation With and Without the BLINT Model. (a) BLINT Model Simulation Shows the Ogival-Nose Rod Penetrating as a Rigid Body. The White Layer Around the Rod Shows the Slip Layer Where Sliding Occurs. (b) Simulation Without the BLINT Model Incorrectly Shows the Ogival-Nose Rod Eroding.



(a)



(b)



(c)

Figure 17. Comparison of Simulations Using the Different Strength Options in Mixed Cells. All Simulations Show Excess Deformation of the Rod and Incorrectly Predict That the Penetrator Will Not Perforate the Target. (a) Yield Strength of Mixed Cell Was Determined by Multiplying the Volume Fractions of Materials That Can Support Shear With the Materials' Yield Strength and Summing Them. (b) Yield Strength of Mixed Cells Was Determined by Multiplying the Volume Fractions of Materials That Can Support Shear With the Materials' Yield Strength, Summing Them, and Dividing by the Sum of Volume Fractions of Materials Supporting Shear. (c) Yield Strength in Mixed Cells Is Zero.

pressure and temperature; (2) all materials are at the same pressure, but the temperature of each material may vary; or (3) all materials may have their own pressure and temperature. Assuming that all materials have the same pressure as in the first two assumptions is obviously incorrect. While pressures may eventually equilibrate, this usually happens over time, not instantaneously. Additionally, assuming all materials have the same pressure can cause problems to arise when fracture is to be modeled using a tension criteria in a cell containing a solid and fluid. The solid will never fail because fluids do not support tension. Assuming thermal equilibrium implies an infinite thermal conductivity. This assumption was used in the CSQII code [48]. The assumption that all materials have their own temperature and pressure on the surface is the most correct; however, additional approximations have to be made. These include assuming the volumetric strain is constant among all materials in a mixed cell. This means, in a mixed cell containing a solid and a gas, the solid would have to accept the same amount of volumetric strain as the gas in spite of the fact that the gas is much more compressible. The approximation correctly allocates PdV work to materials only when compression occurs parallel to a material interface. This assumption is used in the MESA, CTH, and KRAKEN [49] codes. Another approximation used for multiple temperatures and pressures in a mixed cell is that all materials experience equal pressure change. This approximation correctly allocates PdV work among materials only when a cell is compressed perpendicular to the material interfaces and represents an opposite limiting case to constant volumetric strain approximation. This approximation was recently added to the CTH code as a user selectable option [50].

4. Conclusions

Various factors related to material interfaces in Lagrangian and Eulerian shock wave propagation codes, which can lead to disagreement between computations and experience, have been discussed. For Lagrangian codes, interfaces are well defined; however, special logic is needed to prevent interpenetration of two or more bodies. These slide-line algorithms can have user-defined parameters or options that, when incorrectly applied, can lead to considerable error in a computation. For Eulerian codes, interfaces are not well defined and special logic is needed if the interface is to

be known to greater than one cell dimension. Several means of tracking the interfaces and problems associated with them have been discussed. Additionally, Eulerian codes have difficulty treating sliding or material separation. Material properties in mixed cells are treated in an ad hoc manner. Code users should be aware of the problems that can arise in the treatment of material interfaces when they occur so as not to attribute them as reality or new physics.

5. References

1. Zukas, J. A., and D. R. Scheffler. "Practical Aspects of Numerical Simulation of Dynamic Events: Effects of Meshing." *International Journal of Impact Engineering*, to be published.

2. Zukas, J. A., and D. R. Scheffler. "Practical Aspects of Numerical Simulation of Dynamic Events: Constitutive Models and Data." In progress.

3. Zukas, J. A., T. Nicholas, L. B. Greszczuk, H. F. Swift, and D. R. Curran. *Impact Dynamics*. New York: Wiley-Interscience, 1982, Reprinted Melbourne, FL: Krieger Publishing Co., 1992.

4. Zukas, J. A. (editor). *High Velocity Impact Dynamics*. New York: Wiley-Interscience, 1990.

5. Walters, W. P., and J. A. Zukas. *Fundamentals of Shaped Charges*. New York: Wiley-Interscience, 1989, reprinted in Baltimore, MD: CMCPress, 1997.

6. Hallquist, J. O., G. L. Goudreau, and D. J. Benson. "Sliding Interfaces With Contact-Impact in Large-Scale Lagrangian Computations." *Proceeding of the Third International Conference on Finite Elements in Nonlinear Mechanics* (FENOMECH '84), Stuttgart, West Germany, 1984.

7. Belytschko, T., and T. J. R. Hughes (editors). *Computational Methods for Transient Analysis*. Amsterdam: North-Holland, 1992.

8. Schwer, L. E., N. J. Salamon, and W. K. Liu (editors). "Computational Techniques for Contact, Impact, Penetration and Perforation of Solids." AMD-vol. 103. New York: American Society of Mechanical Engineers, 1989.

9. Kulak, R. F., and L. E. Schwer (editors). *Computational Aspects of Contact, Impact and Penetration*. Lausanne: Elmepress International, 1991.

10. Hallquist, J. O. "A Numerical Treatment of Sliding Interfaces and Impact." *Computational Techniques for Interface Problems*, AMD-vol. 30, pp. 117–134, K. C. Park and D. K. Gartling (editors), New York: American Society of Mechanical Engineers, 1978.

11. Neal, M. O. "Contact-Impact by the Pinball Algorithm With Penalty, Projection, and Augmented Lagrangian Methods." PhD dissertation, Northwestern University, 1989.

12. Zukas, J. A., and S. B. Segletes. *ZeuS Technical Description and User's Manual*. Towson, MD: Computational Mechanics Consultants, Inc., 1989.

13. Diekhoff, H. J., B. Fiessler, G. Hausmann, F. Scharpf, and H. J. Schittke. Internal Documentation, Industrieanlagen-Betriebsgesellschaft mbH, Ottobrunn, Germany.

14. Hallquist, J. O. "User's Manuel for DYNA2D an Explicit Two-Dimensional Hydrodynamic Finite Element Code With Interactive Rezoning and Graphical Display." UCID-18756, rev. 3, Lawrence Livermore National Laboratory, Livermore, CA, 1988.

15. Hallquist, J. O. "Theoretical Manual for DYNA3D." UCID-19401, Lawrence Livermore National Laboratory, Livermore, CA, 1983.

16. Johnson, G. R. "EPIC-2, a Computer Program for Elastic-Plastic Impact Computations in Two Dimensions Plus Spin." ARBRL-CR-00373, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1978.

17. Johnson, G. R. "EPIC-3, a Computer Program for Elastic Plastic Impact Calculations in Three Dimensions." ARBRL-CR-343, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1977.

18. Taylor, L.M., and D. P. Flanagan. "PRONTO 3D, a Three-Dimensional Transient Solid Dynamics Program." SAND87-1912, Sandia National Laboratories, Albuquerque, NM, 1989.

19. Goudreau, G. L., and J. O. Hallquist. "Recent Developments in Large-Scale Finite Element Lagrangian Hydrocode Technology." *Computer Methods in Applied Mechanics and Engineering*, vol. 33, nos. 1–3, pp. 725–757, 1982.

20. Breidenbach, R. F., S. R. Jones, V. M. Smith, and B. L. Yaney. "High Speed Impact and Penetration Problems." *Structures Under Extreme Loading Conditions 1997*, PVP-vol. 351, Y. S. Shin, J. A. Zukas, H. S. Levine, and D. M. Jerome (editors), New York: American Society of Mechanical Engineers, 1997.

21. Grove, D. J., A. M. Rajendran, and K. P. Walsh. "Numerical Simulations of Tungsten Projectiles Penetrating Titanium Targets." *Proceedings of the International Conference on Plasticity*, A. S. Khan (editor), Juneau, AK, 1997.

22. Johnson, G. R., and W. H. Cook. "A Constitutive Model and Data for Metals Subjected to Large Strains, High Strain Rates and High Temperatures." *Proceedings of the Seventh International Symposium of Ballistics*, pp. 541–548, The Hague, Netherlands, 1983.

23. Johnson, G. R., and W. H. Cook. "Fracture Characteristics of Three Metals Subjected to Various Strains, Strain Rates, Temperatures, and Pressures." *Journal of Engineering Fracture Mechanics*, vol. 21, no. 1, pp. 31–48, 1985.

24. Burkins, M. S., J. I. Paige, and J. S. Hansen. "A Ballistic Evaluation of Ti-6Al-4V vs. Long Rod Penetrators." ARL-TR-328, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, 1994.

25. Walters, W. P., and J. A. Zukas. *Fundamentals of Shaped Charges*. New York: Wiley-Interscience, 1989.

26. Weickert, C. A. "Evaluation of Selected Computer Codes for Impact and Explosive Detonation Calculations." Memorandum 1059, Defence Research Establishment, Suffield, 1983.

27. Kimsey K. D., and J. A. Zukas. "Contact Surface Erosion for Hypervelocity Problems." BRL-MR-3495, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1986.

28. Zukas, J. A., and S. B. Segletes. "Hypervelocity Impact On Space Structures." *Dynamic Response of Structures to High-Energy Excitations*, AMD-vol. 127/PVP-vol. 225, T. L. Geers and Y. S. Shin (editors), New York: American Society of Mechanical Engineers, 1991.

29. Segletes, S. B., and J. A. Zukas. "The Contact/Erosion Algorithm in the ZeuS Hydrocode." *Contact Mechanics: Computational Techniques*, M. H. Aliabadi and C. A. Brebbia (editors), Southampton: Computational Mechanics Publications, 1993.

30. Brach, R. M. *Mechanical Impact Dynamics: Rigid Body Collisions.* New York: Wiley-Interscience, 1991.

31. Walsh, J. M. Personal communication. Santa Fe, NM, September 1996.

32. Cagliostro, D. J., D. A. Mandell, L. A. Schwalbe, T. F. Adams, and E. J. Chapyak. "MESA 3-D Calculations of Armor Penetration by Projectiles With Combined Obliquity and Yaw." *International Journal of Impact Engineering*, vol. 10, nos. 1–4, pp. 81–92, 1990.

33. Walsh, J. M. "HELP, A Multiple-Material Eulerian Program for Compressible Fluid and Elastic-Plastic Flows in Two Space Dimensions and Time." 3SR-350, Systems, Science and Software, 1970.

34. Burstein, S. Z., H. S. Schechter, and E. L. Turkel. "A Second Order Numerical Model for High Velocity Impact Phenomena." BRL-CR-239, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1975.

35. Burstein, S. Z., H. S. Schechter, and E. L. Turkel. "SMITE - A Second Order Eulerian Code for Hydrodynamic and Elastic-Plastic Problems." BRL-CR-255, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1975.

36. Burstein, S. Z., and H. S. Schechter. "A Second Order Numerical Code for Plane Flow Approximation of Oblique Impact." BRL-CR-294, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1976.

37. Bustein, S. Z., and H. S. Schechter. "Fracture Modeling in the SMITE Code." BRL-CR-295, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1976.

38. Noh, W. F., and P. Woodward. "SLIC (Simple Line Interface Calculation)." *Lecture Notes in Physics*. A. I. Van de Vooren and P. J. Zandbergen (eds.), vol. 59, pp. 330–340, Berlin: Springer-Verlag, 1976.

39. Youngs, D. L. "An Interface Tracking Method for a 3-D Eulerian Hydrodynamics Code." AWRE/44/92/35, UK Atomic Weapons Establishment, 1987.

40. Bell, R. L., and E. S. Hertel Jr. "An Improved Material Interface Reconstruction Algorithm for Eulerian Codes." SAND92-1716, Sandia National Laboratories, Albuquerque, NM, 1992.

41. McGlaun, J. M., S. L. Thompson, and M. G. Elrick. "CTH: A Three-Dimensional Shock Wave Physics Code." *International Journal of Impact Engineering*, vol. 10, nos. 1–4, pp. 351–360, 1990.

42. Benson, D. J. "Computational Methods in Lagrangian and Eulerian Hydrocodes." *Computer Methods in Applied Mechanics and Engineering*, vol. 99, pp. 235–394, 1992.

43. Silling, S. A. "CTH Reference Manual: Boundary Layer Algorithm for Sliding Interfaces in Two Dimensions." SAND93-2487, Sandia National Laboratories, Albuquerque, NM, 1994.

44. Kmetyk, L. N., and P. Yarrington. "CTH Analyses of Steel Rod Penetration Into Aluminum and Concrete Targets With Comparisons to Experimental Data." SAND94-1498, Sandia National Laboratories, Albuquerque, NM, 1994.

45. Scheffler, D. R. "CTH Hydrocode Simulations of Hemispherical and Ogival Nose Tungsten Alloy Penetrators Perforating Finite Aluminum Targets." *Structures Under Extreme Loading Conditions*, PVP-vol. 325, pp. 125–136, Y. S. Shin and J. A. Zukas (editors), New York: American Society of Mechanical Engineers, 1996.

46. Scheffler, D. R., and L. S. Magness Jr. "Target Strength Effects on the Predicted Threshold Velocity for Hemi- and Ogival-Nose Penetrators Perforating Finite Aluminum Targets." *Structures Under Shock and Impact V* (SUSI98), pp. 285–298, N. Jones, D. G. Talaslidis, C. A. Brebbia, and G. D. Manolis (editors), Southampton: Computational Mechanics Publications, 1998.

47. Walker, J. D., and C. E. Anderson Jr. "Multi-Material Velocities for Mixed Cells." In *High-Pressure Science and Technology - 1993*, pp. 1773–1776, S. C. Schmidt, J. W. Shaner, G. A. Samara, and M. Ross (editors), Woodbury, NY: American Institute of Physics, 1994.

48. Thompson, S. L. "CSQII - An Eulerian Finite Difference Program for Two-Dimensional Material Response - Part 1. Material Sections." SAND77-1339, Sandia National Laboratories, Albuquerque, NM, 1979.

49. DeBar, R. B. "Fundamentals of the KRAKEN Code." UCID-17366, University of California Lawrence Livermore National Laboratory, Livermore, CA, 1974.

50. Farnsworth, A. V., Jr. "CTH Reference Manual: Cell Thermodynamics Modifications and Enhancements." SAND95-2394, Sandia National Laboratories, Albuquerque, NM, 1995.

INTENTIONALLY LEFT BLANK.

NO. OF COPIES	ORGANIZATION
2	DEFENSE TECHNICAL INFORMATION CENTER DTIC DDA 8725 JOHN J KINGMAN RD STE 0944 FT BELVOIR VA 22060-6218
1	HQDA DAMO FDT 400 ARMY PENTAGON WASHINGTON DC 20310-0460
1	OSD OUSD(A&T)/ODDDR&E(R) R J TREW THE PENTAGON WASHINGTON DC 20301-7100
1	DPTY CG FOR RDA US ARMY MATERIEL CMD AMCRDA 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001
1	INST FOR ADVNCD TCHNLGY THE UNIV OF TEXAS AT AUSTIN PO BOX 202797 AUSTIN TX 78720-2797
1	DARPA B KASPAR 3701 N FAIRFAX DR ARLINGTON VA 22203-1714
1	NAVAL SURFACE WARFARE CTR CODE B07 J PENNELLA 17320 DAHLGREN RD BLDG 1470 RM 1101 DAHLGREN VA 22448-5100
1	US MILITARY ACADEMY MATH SCI CTR OF EXCELLENCE MADN MATH MAJ HUBER THAYER HALL WEST POINT NY 10996-1786

NO. OF COPIES	ORGANIZATION
1	DIRECTOR US ARMY RESEARCH LAB AMSRL D D R SMITH 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	DIRECTOR US ARMY RESEARCH LAB AMSRL DD 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	DIRECTOR US ARMY RESEARCH LAB AMSRL CI AI R (RECORDS MGMT) 2800 POWDER MILL RD ADELPHI MD 20783-1145
3	DIRECTOR US ARMY RESEARCH LAB AMSRL CI LL 2800 POWDER MILL RD ADELPHI MD 20783-1145
1	DIRECTOR US ARMY RESEARCH LAB AMSRL CI AP 2800 POWDER MILL RD ADELPHI MD 20783-1197
	ABERDEEN PROVING GROUND
4	DIR USARL AMSRL CI LP (BLDG 305)

NO. OF COPIES	ORGANIZATION
1	US ARMY DUSA OPS RSCH D WILLARD 102 ARMY PENTAGON WASHINGTON DC 20310-0102
5	DEFENSE NUCLEAR AGENCY MAJ J LYON CDR K W HUNTER T FREDERICKSON R J LAWRENCE SPSP K KIBONG 6801 TELEGRAPH RD ALEXANDRIA VA 22310-3398
3	COMMANDER US ARMY ARDEC AMSTA AR FSA E W P DUNN J PEARSON E BAKER PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR CCH V M D NICOLICH PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC E ANDRICOPOULOS PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER USA STRATEGIC DEFNS CMD CSSD H LL T CROWLES HUNTSVILLE AL 35807-3801
3	COMMANDER US ARMY AVIATION & MISSLE CMD AMSAM RD PS WF S HILL D LOVELACE M SCHEXNAYDER REDSTONE ARSENAL AL 35898-5247
1	MIS DEFNS & SPACE TECHNOLOGY CSSD SD T K H JORDAN PO BOX 1500 HUNTSVILLE AL 34807-3801
3	COMMANDER US ARMY RESEARCH OFFICE K IYER J BAILEY S F DAVIS PO BOX 12211 RESEARCH TRIANGLE PARK NC 27709
1	NAVAL AIR WARFARE CTR S A FINNEGAN BOX 1018 RIDGECREST CA 93556
4	COMMANDER NAVAL WEAPONS CENTER N FASIG CODE 3261 T T YEE CODE 3263 D THOMPSON CODE 3268 W J MCCARTER CODE 6214 CHINA LAKE CA 93555
12	COMMANDER NAVAL SURFACE WARFARE CTR DAHLGREN DIVISION H CHEN D L DICKINSON CODE G24 C R ELLINGTON C R GARRETT CODE G22 W HOLT CODE G22 W E HOYE G22 R MCKEOWN J M NELSON M J SILL CODE H11 WILLIAM J STROTHER A B WARDLAW JR L F WILLIAMS CODE G33 17320 DAHLGREN RD DAHLGREN VA 22448

NO. OF COPIES	ORGANIZATION
5	AIR FORCE ARMAMENT LAB AFATL DLJW W COOK M NIXON AFATL DLJR J FOSTER AFATL MNW LT D LOREY R D GUBA EGLIN AFB FL 32542
1	USAF PHILLIPS LABORATORY VTSI ROBERT ROYBAL KIRTLAND AFB NM 87117-7345
2	USAF PHILLIPS LABORATORY PL WSCD F ALLAHDADI PV VTA D SPENCER 3550 ABERDEEN AVE SE KIRTLAND AFB NM 87117-5776
5	WRIGHT LABS MNMW J W HOUSE ARMAMENT DIRECTORATE STE 326 B1 R D HUNT B MILLIGAN B C PATTERSON W H VAUGHT 101 W EGLIN BLVD EGLIN AFB FL 32542-6810
1	AFIT ENC D A FULK WRIGHT PATTERSON AFB OH 45433
6	LOS ALAMOS NATIONAL LABORATORY L HULL MS A133 J V REPA MS A133 C WINGATE MS D413 E J CHAPYAK MS F664 P HOWE MS P915 J KENNEDY MS P915 PO BOX 1663 LOS ALAMOS NM 87545

NO. OF COPIES	ORGANIZATION
39	SANDIA NATIONAL LABORATORIES ATTN MAIL SERVICES MS-0100 E W REECE MS 0307 D P KELLY MS 0307 L WEIRICK MS 0327 R TACHAU MS 0425 D LONGCOPE MS 0439 D HAYES MS 0457 J ASAY MS 0458 W TEDESCHI MS 0482 J SCHULZE MS 0483 P A LONGMIRE MS 0560 J COREY MS 0576 E S HERTEL JR MS 0819 A ROBINSON MS 0819 T TRUCANO MS 0819 J M MCGLAUN MS 0819 M VIGIL MS 0819 R BRANNON MS 0820 J ANG MS 0821 M BOSLOUGH MS 0821 L CHHABILDAS MS 0821 D CRAWFORD MS 0821 M FURNISH MS 0821 C HALL MS 0821 W REINHART MS 0821 P STANTON MS 0821 M KIPP DIV 1533 P YARRINGTON DIV 1533 J MCGLAWA DIV 1541 M FORRESTAL DIV 1551 R LAFARGE DIV 1551 C HILLS DIV 1822 R O NELLUMS DIV 9122 P TAYLOR ORG 1432 B LEVIN ORG 7816 L N KMETYK R REEDER J SOUTHWARD C KONRAD K LANG PO BOX 5800 ALBUQUERQUE NM 87185-0100

NO. OF COPIES	ORGANIZATION
3	DIRECTOR LLNL PHYSICS DEPT D A YOUNG T W BARBEE III F J ROGERS LIVERMORE CA 94551
4	DIRECTOR LLNL MS L35 R E TIPTON D BAUM M MURPHY T MCABEE PO BOX 808 LIVERMORE CA 94550
2	DIRECTOR LLNL MS L125 D R FAUX N W KLINO PO BOX 808 LIVERMORE CA 94550
1	DIRECTOR LLNL R BARKER L159 PO BOX 808 LIVERMORE CA 94550
1	DIRECTOR LLNL MS L180 G SIMONSON PO BOX 808 LIVERMORE CA 94550
1	DIRECTOR LLNL F A HANDLER L182 PO BOX 808 LIVERMORE CA 94550
1	DIRECTOR LLNL D WOOD L352 PO BOX 808 LIVERMORE CA 94550

NO. OF COPIES	ORGANIZATION
1	DIRECTOR LLNL S G COCHRAN L389 PO BOX 808 LIVERMORE CA 94550
3	DIRECTOR LLNL MS L495 D GAVEL J HUNTER E JOHANSSON PO BOX 808 LIVERMORE CA 94550
1	DIRECTOR LLNL R M KUKLO L874 PO BOX 808 LIVERMORE CA 94550
4	ENERGETIC MATERIALS RSCH TSTNG CTR NEW MEXICO TECH D J CHAVEZ M LEONE L LIBERSKY F SANDSTROM CAMPUS STATION SOCORRO NM 87801
3	NASA JOHNSON SPACE CENTER E CHRISTIANSEN J L CREWS F HORZ MAIL CODE SN3 2101 NASA RD 1 HOUSTON TX 77058
1	APPLIED RESEARCH LAB J A COOK 10000 BURNETT ROAD AUSTIN TX 78758

NO. OF COPIES	ORGANIZATION
4	SOUTHWEST RESEARCH INSTITUTE C ANDERSON S A MULLIN J RIEGEL J WALKER PO DRAWER 28510 SAN ANTONIO TX 78228-0510
2	AEROJET J CARLEONE S KEY PO BOX 13222 SACRAMENTO CA 95813-6000
2	AEROJET ORDNANCE P WOLF G PADGETT 1100 BULLOCH BLVD SOCORRO NM 87801
3	ALLIANT TECHSYSTEMS INC R STRYK G R JOHNSON MN11-1614 P SWENSONMN11-2720 600 SECOND ST NE HOPKINS MN 55343
1	M L ALME 2180 LOMA LINDA DR LOS ALAMOS NM 87544-2769
2	APPLIED RESEARCH ASSOC INC D GRADY F MAESTAS SUITE A220 4300 SAN MATEO BLVD NE ALBUQUERQUE NM 87110
1	APPLIED RESEARCH LABORATORIES T M KIEHNE PO BOX 8029 AUSTIN TX 78713-8029
1	ATA ASSOCIATES W ISBELL PO BOX 6570 SANTA BARBARA CA 93111

NO. OF COPIES	ORGANIZATION
1	BATTELLE R M DUGAS 7501 S MEMORIAL PKWY SUITE 101 HUNTSVILLE AL 35802-2258
1	BOEING HOUSTON SPACE STN R F GRAVES BOX 58747 HOUSTON TX 77258
5	COMPUTATIONAL MECHANICS CONSULTANTS J A ZUKAS (5 CP) PO BOX 11314 BALTIMORE MD 21239-0314
3	DYNA EAST CORP P C CHOU R CICCARELLI W FLIS 3620 HORIZON DRIVE KING OF PRUSSIA PA 19406
1	R J EICHELBERGER 409 W CATHERINE ST BEL AIR MD 21014-3613
3	ENIG ASSOCIATES INC J ENIG D J PASTINE M COWPERTHWAITE SUITE 500 11120 NEW HAMPSHIRE AVE SILVER SPRING MD 20904-2633
1	EXPLOSIVE TECHNOLOGY M L KNAEBEL PO BOX KK FAIRFIELD CA 94533
1	GB TECH LOCKHEED J LAUGHMAN 2200 SPACE PARK SUITE 400 HOUSTON TX 77258
2	GB TECH LOCKHEED L BORREGO C23C J FALCON JR C23C 2400 NASA ROAD 1 HOUSTON TX 77058

NO. OF COPIES	ORGANIZATION
6	GDLS 38500 MOUND RD W BURKE MZ436 21 24 G CAMPBELL MZ436 30 44 D DEBUSSCHER MZ436 20 29 J ERIDON MZ436 21 24 W HERMAN MZ 435 01 24 S PENTESCU MZ436 21 24 STERLING HTS MI 48310-3200
1	GRC INTERNATIONAL T M CUNNINGHAM 5383 HOLLISTER AVE SANTA BARBARA CA 93111
1	RAYTHEON MSL SYS CO T STURGEON BLDG 805 M/S D4 PO BOX 11337 TUCSON AZ 85734-1337
5	INST OF ADVANCED TECHNOLOGY UNIVERSITY OF TX AUSTIN S J BLESS J CAZAMIAS J DAVIS H D FAIR D LITTLEFIELD 4030-2 W BRAKER LN AUSTIN TX 78759
1	INTERNATIONAL RESEARCH ASSOC D L ORPHAL 4450 BLACK AVE PLEASANTON CA 94566
1	ITT SCIENCES AND SYSTEMS J WILBECK 600 BLVD SOUTH SUITE 208 HUNTSVILLE AL 35802
1	R JAMESON 624 ROWE DR ABERDEEN MD 21001
1	KAMAN SCIENCES CORP D L JONES 2560 HUNTINGTON AVE SUITE 200 ALEXANDRIA VA 22303

NO. OF COPIES	ORGANIZATION
1	D R KENNEDY & ASSOC INC D KENNEDY PO BOX 4003 MOUNTAIN VIEW CA 94040
1	LOCKHEED MARTIN ELEC & MSLS G W BROOKS 5600 SAND LAKE RD MP 544 ORLANDO FL 32819-8907
1	LOCKHEED MARTIN MISSLE & SPACE W R EBERLE PO BOX 070017 HUNTSVILLE AL 35807
3	LOCKHEED MARTIN MISSILE & SPACE M A LEVIN ORG 81 06 BLDG 598 M R MCHENRY T A NGO ORG 81 10 BLDG 157 111 LOCKHEED WAY SUNNYVALE CA 94088
4	LOCKHEED MISSILE & SPACE CO J R ANDERSON W C KNUDSON S KUSUMI 0 81 11 BLDG 157 J PHILLIPS 0 54 50 PO BOX 3504 SUNNYVALE CA 94088
1	LOCKHEED MISSILE & SPACE CO R HOFFMAN SANTA CRUZ FACILITY EMPIRE GRADE RD SANTA CRUZ CA 95060
1	MCDONNELL DOUGLAS ASTRONAUTICS CO B L COOPER 5301 BOLSA AVE HUNTINGTON BEACH CA 92647
1	NETWORK COMPUTING SERVICES INC T HOLMQUIST 1200 WASHINGTON AVE S MINNEAPOLIS MN 55415

NO. OF COPIES ORGANIZATION

4 ORLANDO TECHNOLOGY INC
D A MATUSKA
M GUNGER
J OSBORN
R SZEZEPANSKI
4565 COMMERCIAL DR #A
NICEVILLE FL 32578

1 PHYSICAL SCIENCES INC
P NEBOLSINE
20 NEW ENGLAND BUS CTR
ANDOVER MA 01810

5 PRIMEX TECHNOLOGIES INC
G FRAZIER
L GARNETT
D OLIVER
D TUERPE
J COFFENBERRY
2700 MERCED ST
SAN LEANDRO CA 94577-0599

1 RAYTHEON ELECTRONIC SYSTEMS
R LLOYD
50 APPLE HILL DRIVE
TEWKSBURY MA 01876

1 ROCKWELL INTERNATIONAL
ROCKETDYNE DIVISION
H LEIFER
16557 PARK LN CIRCLE
LOS ANGELES CA 90049

1 ROCKWELL MISSILE SYS DIV
T NEUHART
1800 SATELLITE BLVD
DULUTH GA 30136

1 SAIC
M W MCKAY
10260 CAMPUS POINT DR
SAN DIEGO CA 92121

2 SOUTHERN RESEARCH INSTITUTE
L A DECKARD
D P SEGERS
PO BOX 55305
BIRMINGHAM AL 35255-5305

NO. OF COPIES ORGANIZATION

5 SRI INTERNATIONAL
J D COLTON
D CURRAN
R KLOOP
R L SEAMAN
D A SHOCKEY
333 RAVENSWOOD AVE
MENLO PARK CA 94025

1 ZERNOW TECHNICAL SVCS INC
L ZERNOW
425 W BONITA AVE SUITE 208
SAN DIMAS CA 91773

ABERDEEN PROVING GROUND

52 DIR USARL
AMSRL WM, I MAY
AMSRL WM BC
A ZIELINSKI
AMSRL WM BE
S L HOWARD
AMSRL WM BD
R PESCE-RODRIGUEZ
A J KOTLAR
AMSRL WM MB
G GAZONAS
AMSRL WM MC
J M WELLS
AMSRL WM T
B BURNS
T W WRIGHT
AMSRL WM TA
M BURKINS
W GILLICH
W BRUCHEY
G FILBEY
W A GOOCH
H W MEYER
E J RAPACKI
J RUNYEON
D KLEPONIS
AMSRL WM TB
R FREY
P BAKER
R LOTTERO
J STARKENBERG

NO. OF
COPIES ORGANIZATION

ABERDEEN PROVING GROUND (CONTINUED)

AMSRL WM TC
T W BJERKE
R COATES
K KIMSEY
M LAMPSON
D SCHEFFLER (10 CP)
S SCHRAML
G SILSBY
B SORENSEN
R SUMMERS
W WALTERS
AMSRL WM TD
A M DIETRICH
D DANDEKAR
K FRANK
M RAFTENBERG
A RAJENDRAN
G RANDERS-PEHRSON LLNL
M SCHEIDLER
S SCHOENFELD
S SEGLETES
T WEERISOORIYA
AMSRL WM TE
J POWELL
A PRAKASH

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 2000	Final, May–Dec 99

4. TITLE AND SUBTITLE
Practical Aspects of Numerical Simulations of Dynamic Events: Material Interfaces

5. FUNDING NUMBERS
622618AH80

6. AUTHOR(S)
Daniel R. Scheffler and Jonas A. Zukas*

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMRSR-WM-TC
Aberdeen Proving Ground, MD 21005-5066

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-2302

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

10.SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
*Computational Mechanics Consultants, Inc., P.O. Box 11314, Baltimore, MD 21239-0314

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The use of finite-difference and finite-element computer codes to solve problems involving fast, transient loading is commonplace. A large number of commercial codes exist and are applied to problems ranging from fairly low to extremely high damage levels (e.g., design of containment structures to mitigate effects of industrial accidents; protection of buildings and people from blast and impact loading; foreign-object impact damage; design of space structures to withstand impacts of small particles moving at hypervelocity, a case where pressures generated exceed the material strength by an order of magnitude). But, what happens if code predictions do not correspond with reality? This report discusses various factors related to material interfaces in Lagrangian and Eulerian shock wave propagation codes (hydrocodes), which can lead to disagreement between computations and experience. Companion reports focus on problems associated with meshing and constitutive models and the use of material data at strain rates inappropriate to the problem. This report is limited to problems involving fast, transient loading, which can be addressed by commercial finite-difference and finite-element codes.

This report has been accepted for publication in a future volume of the *International Journal of Impact Engineering*.

14. SUBJECT TERMS	15. NUMBER OF PAGES
high-velocity impact, fast transient loading, numerical methods, material interfaces, Lagrangian methods, Eulerain methods, finite difference, finite elements	50
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIEED	UL

INTENTIONALLY LEFT BLANK.